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GRILLAGE CORROSION SURVEYS USING THE TOWER LEG INTEGRITY MONITOR - 1989 RESULTS

Report No 90-88-K

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ABSTRACT

A corrosion survey of grillage footings was conducted as part of the Transmission Line Refurbishment Program. A total of 500 tower sites were examined during this survey representing approximately 20% of the steel structures along 15 separate transmission lines. Most of the grillages examined were from towers aged 60 to 80 years, located in Western and Central Regions. The survey included corrosion potential and corrosion current measurements by means of a Tower Leg Integrity Monitor (TLIM), visual inspections of grillage steel just below ground line and occasional detailed inspections down to the grillage pad. The main findings of the survey are that a large portion of the grillages inspected were still in good condition and the corrosion currents were low, being less than or equal to 1 mA. Based on corrosion potential measurements, the galvanizing layer on most of the older grillages has corroded away. The stub angles of the older footings were reinforced with new, galvanized angles at ground line during the 1930's. The TLIM is rugged and reliable in the field and provides data which helps clarify the nature of corrosion activity on underground steel. However, because of the TLIM's limitations, it should not be used as a "one-time" diagnostic tool. Rather, it should be incorporated into a regular corrosion monitoring program for the older grillage footings.

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GRILLAGE CORROSION SURVEYS USING THE TOWER LEG INTEGRITY MONITOR - 1989 RESULTS

1.0 INTRODUCTION

As part of the transmission line refurbishment program, extensive footing corrosion surveys were conducted in 1988-89 of several 115-kV and 230-kV transmission lines in southern Ontario. The in-service dates of these transmission lines range from 1910 to 1932 and these lines are, in most part, located in Central and Western Regions. Table I provides a list of all transmission lines surveyed in 1988-89. Since the results of corrosion surveys conducted in 1988 have been reported elsewhere/1,2/, this report only summarizes results of surveys conducted in 1989.

When constructed in soil, the footings of old 115-kV and 230-kV transmission towers consist of steel grillages buried approximately 6 to 8 ft (1.8 to 2.4 m) below ground surface. As with most buried steel structures (ie pipelines, fuel tanks, steel piles, buried cables, etc), the process of underground corrosion will eventually lead to metal loss which could significantly affect the integrity of the structures. In the case of grillage footings, metal loss could lead to reduced cross-sectional areas of steel members thereby significantly reducing their load carrying capacity. From the refurbishment point of view, the objective of the footing corrosion surveys was to determine the general condition of buried steel grillages from some of the oldest transmission lines in southern Ontario. The results of such surveys would help determine the overall severity of the underground corrosion problem related to transmission tower footings as well as identify specific problem lines which might require strengthening or replacement of grillage footings.

Footing corrosion surveys have been conducted in the past in both Eastern and Central Regions. However, these surveys have not continued on a routine basis and therefore do not provide any data on the time-dependent effects of underground corrosion. The data from these surveys consist of leg-to-soil potential measurements along with a general classification of the soil type in the immediate vicinity. For the most part, these results are 10 or more years old.

For the present surveys, a Tower Leg Integrity Monitor (TLIM) manufactured by Cormon Ltd of England was utilized which allows measurements of corrosion potentials and corrosion currents. The measurement of corrosion currents has been used with some success in England to detect corrosion problems on transmission tower footings. However, these tower footings consist of concreted steel structures which are significantly different from the steel grillages used by Ontario Hydro. Since the electrochemical principles implemented by the TLIM are applicable to all buried steel, an additional objective of the present surveys was to assess the usefulness of this device in detecting underground corrosion of grillage footings.

2.0 METHODOLOGY

2.1 Tower Leg Integrity Monitor

The Cormon TLIM 100 is a self contained inspection tool capable of monitoring the condition of galvanized steel structures embedded in soil and/or concrete. The TLIM is based on an electrochemical technique known as the polarization-resistance method originally proposed by Stern/3/. The method predicts that a linear (ohmic) relationship exists between polarization (potential change) and polarizing current at changes less than 20 mV. The open circuit corrosion current, I_{corr} is then proportional to the inverse polarization resistance R_p as,

$$I_{corr} = \frac{K}{R_p} = \frac{K.\Delta I}{\Delta E} \qquad \text{.......... (1)}$$

where, K = proportionality, constant calculated from other polarization data
ΔI = imposed polarization current
ΔE = change in open circuit electrode potential (<20 mV)

Theoretical analysis of the shape of polarization curves by Stern and Geary/4/ showed that,

$$K = \frac{\beta a\, \beta c}{2.3(\beta a + \beta c)} \qquad \text{.......... (2)}$$

where βa = anodic Tafel slope
βc = cathodic Tafel slope

An example of polarization curves and associated βa and βc values are shown in Figure 1. For the rusting of steel, K has been determined by the Central Electricity Generating Board (CEGB) to be 9 mV/5/. This value has been used during the present surveys to convert the inverse polarization resistance to corrosion current in mA as shown by Equation 1.

The TLIM operates by passing a small electrical current between the galvanized grillage leg and a probe inserted into the ground nearby (Figure 2). These currents perturb the electrochemical processes at any active corrosion sites and the resulting changes in potential of the leg are measured with reference to a Cu-$CuSO_4$ half cell in contact with the ground close to the leg. As shown by Equation 1, the greater the active corrosion, the greater the injected current required to displace the leg potential.

2.2 Field Measurements

Because of the large number of transmission lines to be examined during the 1989 field season, it was decided that only every 5th tower along a line would be surveyed. Depending on the use and condition of the terrain along the transmission line right-of-way, the following methods were used to access the towers in question: pick-up truck, four-wheel-drive ATV, or on foot. Upon reaching the tower, the TLIM was used to obtain corrosion potential (E_{corr}) and corrosion current (I_{corr}) measurements from all four footings. The layout used for the measurements is shown in Figure 2 and the TLIM 100 is shown in Figure 3. Due to the proximity of the reference half-cell and ground probe to the grillage leg (< 1 m), it would seem that potential and current measurements obtained in this way are representative of the near surface steel characteristics. Concurrently with the TLIM measurements, a shallow excavation of approximately 1 to 2 ft (30 to 60 cm) was made around one selected tower leg. This excavation was used to examine the near surface grillage steel where it was assumed that the most severe corrosion would have taken place. The degree of surface corrosion was rated and photographs were taken at selected sites. Soil samples were also obtained during the excavation and returned to the laboratory for further testing. Under normal weather and terrain conditions, two technicians could perform this type of survey at a rate of 12 to 15 towers per day.

2.3 Laboratory Measurements

Laboratory tests were conducted on collected soil samples to determine the degree of corrosivity of the various soil types encountered during the surveys. Several soil parameters can contribute to the degree of corrosivity of a given soil/6/: resistivity, moisture content, oxygen content, pH, chloride ion content, sulphide ion content, sulphate ion content, corrosion-activating bacteria, total hardness and redox potential.

The influence of some of the soil parameters listed above can be taken into account by the measurement of a single parameter. Consequently, only the following soil properties were measured during this survey, as suggested by Environment Canada/10/: soil resistivity, pH, moisture content and sulphides. The following influences are associated with these four properties:

1. the higher the resistivity of the soil, the lower the corrosion rate,
2. the lower the pH (< 7.0), the greater the corrosion rate,
3. soil moisture content is normally directly related to corrosion rate, and
4. the presence of sulphides is often an indicator of sulphate-reducing bacteria which acts as a catalyst in the corrosion process.

The following laboratory tests were conducted on the samples:

1) soil resistivity using the Miller soil box as in ASTM G57 (see Figure 4),
2) soil pH measurements using a standard pH probe immersed in a slurry of 50 g of soil and 125 mL of distilled water,
3) the presence of sulphide was detected by mixing a small amount of soil with 15% HCl solution in a test tube then inserting a lead acetate strip,
4) moisture content using a gravimetric method as in ASTM D-2216.

The results of the laboratory testing are reported in tabular form along with the field survey results for each tower line inspected.

Several environmental conditions will also contribute to underground corrosion and in some cases may be even more important than the degree of soil corrosivity. These are soil permeability, degree of soil disturbance, position of the water table, and presence of stray DC currents. The influence of some of these factors is discussed in the appendix. Several researchers have concluded that no unique relationship exists between individual or grouped soil parameters and degree of corrosion/7,8,9/. The measurement of these soil parameters can, at best, be used in identifying potentially corrosive environments where further testing may be conducted. They should not be used uniquely for the identification of problem areas.

3.0 CORROSION SURVEY DATA

3.1 Data Presentation

The result of each grillage corrosion survey is reported in the appendix along with a brief discussion of the general corrosion condition of the tower line footings in question. The data obtained during the surveys are provided in tabular form and specific values are plotted for analysis purposes. In the case of corrosion potential (E_{corr}) and corrosion current (I_{corr}) values, the four measurements obtained for each tower site have been averaged such that only one E_{corr} and one I_{corr} are associated with each tower. This method of reducing the number of data points to be handled during the analysis was justified by the fact that, in general, the values from all four footings of a particular tower were similar. For the most important case of one footing having a higher I_{corr} than the remaining three, the average I_{corr} would still reflect this anomaly. The following sections provide some background information on the type of data collected during the surveys.

3.2 Corrosion Potential Readings

The open circuit electrode potential (E_{corr}) exhibited by a metal in contact with soil has been used extensively as a method of qualitative assessment of corrosion conditions. Most notably, E_{corr} measurements, universally obtained with reference to a copper-copper sulphate ($Cu\text{-}CuSO_4$) half cell, have been used regularly by the oil and gas industry for monitoring the condition of buried steel pipelines and underground storage tanks. Potential measurements are also used routinely for designing, monitoring and troubleshooting of cathodic protection systems of both sacrificial anode and rectifier types.

The measurement of leg-to-soil potentials coupled with occasional visual inspections has formed the basis for the most previous corrosion surveys undertaken by Ontario Hydro personnel. The assessment of degree of corrosion from leg-to-soil potentials is based on the criteria that galvanized steel will exhibit a potential with respect to $Cu\text{-}CuSO_4$ of approximately -0.75 to -0.8 volts. Following the deterioration of the zinc layer during active corrosion, the potential of the steel leg will increase to -0.4 to -0.45 volts. Transmission line tower steel used by Ontario Hydro is always galvanized, ie coated with zinc. Since zinc will corrode much easier than steel, the galvanizing layer will act to protect the tower steel from corrosion. Galvanized steel footings could exhibit leg-to-soil potentials as low as -0.8 to -1.0 volts. Potentials within this range imply that the galvanizing layer is still acting as a protective coating.

In summary, measurement of leg-to-soil potentials provide an indication of the present state of the grillage steel after having sustained the cumulative effects of underground corrosion. With time, barring any external effects such as cathodic protection, leg-to-soil potentials will become more electropositive, ie go from -0.8 to -0.4 volts. Because of the method used to measure leg-to-soil potentials, these values tend to represent the effects of generalized corrosion. Localized corrosion, such as within individual pits, will be very difficult to detect unless pitting corrosion is occurring over a large surface area. In addition, leg-to-soil potentials do not provide an indication of the rate of corrosion activity. This may only be qualitatively assessed if potential surveys are undertaken periodically along the same transmission line.

3.3 Corrosion Current Readings

The polarization resistance technique provides a measure of corrosion current, I_{corr}, which can be used more readily to estimate corrosion rate. When a metal is exposed to a given environment, it will acquire a certain corrosion potential at which the anodic current, due to metal dissolution, is numerically equal to cathodic current, due to the reduction of the oxidation agent. These two processes are represented by the following:

$$M \quad M^{+} + e^{-} \qquad \text{..........(3)}$$

$$Z^{++} + e^{-} \quad Z^{+} \qquad \text{..........(4)}$$

Equation 3 corresponds to anodic dissolution and Equation 4 to cathodic reduction. For the case of steel corrosion underground, the oxidation reactions at the anode surface involve the ionization of metal by

$$Fe \quad Fe^{++} + 2e \qquad \text{..........(5)}$$

This reaction represents the corrosion of steel and formation of rust. Several reduction reactions can occur at the cathode surface depending on the nature of the electrolyte. These reactions are:

$2H^+ + 2e \quad H_2$ in acid solutions ....(6)
$4H^+ + O_2 + 4e \quad 2H_2O$ in oxygenated acid solutions ....(7)
$2H_2O + O_2 + 4e \quad 4OH^-$ in neutral solutions ....(8)

The rates of these reactions are represented by current densities I_a and I_c which correspond to the corrosion current, I_{corr}/11/.

From the above explanation, it may be concluded that I_{corr} should represent the magnitude of corrosion activity taking place at the time of measurement. Ideally, as suggested in the Cormon manual/5/, corrosion surveys should be conducted in the spring and/or autumn, since the soil's moisture content will be higher during these periods, promoting the highest corrosion activity. This particular issue has been addressed in a previous report/2/ which presented the results of a corrosion survey on an old tower line through Oakville. There were no substantial differences between corrosion currents measured in August and the following November. This could have been due to the fact that the thickness of the drying/rewetting zone was not great enough to influence the overall corrosion activity of the grillage footings.

To calculate the rate of metal loss from corrosion survey data, one must employ an empirical correlation procedure such as used by Moore/12/, or make an assessment of the nature of the corrosion activity, ie general or localized corrosion. In this latter procedure, one must assume an area of influence associated with the measured corrosion current and couple that with a known rate of metal dissolution in mm/A/yr. Empirical procedures tend to correlate a certain percentage of visible corrosion with actual measured data such as E_{corr} and I_{corr}. The danger of this approach is that a significant amount of corrosion may have occurred in the past but since corrosion activity is known to decrease with time under normal circumstances/11,13/, the "one-shot" electrochemical measurements could prove very misleading. This points out the importance of obtaining long-term E_{corr} and I_{corr} measurements to allow an adequate assessment of corrosion damage.

3.4 Soil Resistivity Measurements

Soil resistivity measurements were made on soil samples from selected tower sites to assess the relative corrosivity of the various soil types encountered during the surveys. These measurements were made using the Miller soil box and fully saturated soil samples. This measurement procedure would provide the lowest or worst-case soil resistivity values. Although it has been difficult in the past to correlate absolute soil resistivity values with actual corrosion damage, the following relationships provide a qualitative assessment of soil corrosivity/14/:

Soil Resistivity, Ω-cm	Soil Corrosivity
0 to 2,000	very corrosive
2,000 to 5,000	corrosive
5,000 to 10,000	moderately corrosive
10,000 to 15,000	mildly corrosive

4.0 RESULTS OF DETAILED INVESTIGATIONS

As part of the corrosion studies conducted in 1989, three detailed investigations were completed: 1) detailed visual examination of four grillages from circuit M31A in Ottawa, 2) an interference survey along circuit K6Z near Windsor, and 3) a detailed visual inspection of four grillages from an Oakville tower line.

The rationale for conducting the grillage inspections was that the removal of towers from the lines in question provided the opportunity to correlate the TLIM readings to actual levels of corrosion. The interference survey along K6Z was initiated to try and explain the occurrence of unusually high corrosion currents measured during the routine corrosion survey.

The results of the routine corrosion surveys for circuits M31A and K6Z are reported in the appendix.

4.1 Visual Examination of Grillages from M31A (In-Service Date = 32.10.20)

Based on corrosion potential (E_{corr}) and corrosion current (I_{corr}) measurements taken during a survey from April 24 to 26, 1989, four footings were completely excavated for visual examination. Towers 330 and 331 had high corrosion current readings at 1.24 and 1.43 mA respectively. Towers 335 and 337 had low current readings at 0.3 mA. The corrosion potentials were at -0.76 V for Towers 330, 332 and 335 and -0.65 V for 337. These potential readings indicate that the galvanizing layer on all the towers was still in good condition.

On June 19, 1989, one footing from each of the selected tower sites was removed. Prior to excavation, corrosion potential and corrosion current measurements were repeated on the grillages.

Tower No	April 24, 1989		June 19, 1989	
	E_{corr} (mV)	I_{corr} (mA)	E_{corr} (mV)	I_{corr}(mA)
330	-0.773	2.05	-0.774	1.82
331	-0.756	2.02	-0.808	1.35
335	-0.748	0.31	-0.797	0.90
337	-0.587	0.34	-0.767	1.41

NOTE: In April, Towers 330 and 331 were still intact and conductors were still on.
In June, Tower 337 had been already cut off 1 m below ground surface.

The ASTM Standard for the weight of zinc coating on 1/4" thick hot dip galvanized products is 2.3 ounces per square foot of surface. This is equivalent to a coating thickness of 0.0039 inch or 3.9 mils. A magnetic gauge was used to measure the thickness of zinc coating on the footings excavated.

Tower 330 exhibited the worst surficial corrosion, as shown in Figure 5, within the channel section above the grillage pad. The coating thickness along this section ranged from 0.2 to 3.8 mils. At all other testing locations on the grillage, the zinc coating was 4.0 mils thick or greater, which still meets the ASTM Standard even after 57 years of burial. Figure 6 shows a grillage footing from Tower 331. Some minor corrosion has occurred along the channel section above the grillage. Galvanizing thickness was measured at 3.2 mils along the main stub just below ground line. In general the thickness of zinc coating was well above the 3.9 mils standard at most locations on the footing.

Figure 7 shows a grillage footing from Tower 335 which appears completely free of corrosion products. The smallest thickness of galvanizing was 3.5 mils measured at 50 cm above ground line.

Figure 8 shows a grillage footing from Tower 337. This grillage footing is narrower than the other three and was anchored into the shale bedrock with 3, 1.5" diameter anchor bolts. Surficial corrosion has discoloured most of the grillage stub and galvanizing thickness has reduced to 2.8 mils approximately 60 cm above the pad. Localized corrosion has also occurred along the channel section and angle iron bolted to the top of the pad.

All four grillages examined appeared to be structurally sound and had only suffered from localized surficial corrosion. In most cases, the thickness of galvanizing along the grillage members exceeded the minimum ASTM standard of 3.9 mils. The worst case of surficial corrosion was found within the channel above the grillage pad of Tower 330. This happens to correlate well with the local soil characteristics which exhibited the lowest resistivity (4350 ohm-cms) and lowest pH (6.0) of all four tower sites examined.

In conclusion, the corrosion potentials (E_{corr}) and corrosion currents (I_{corr}) obtained during the survey indicated that after 57 years of burial, there was a minor amount of corrosion taking place, but that in general the steel was intact and in some cases the galvanizing layer was still protecting the steel. Visual inspections of grillage stubs just below ground line (60 cm) revealed that little or no visible corrosion of the steel had taken place. Four grillage footings were selectively removed and transported back to the laboratory for closer visual inspection and testing. The results of this inspection indicated that enough galvanizing remained on most of the grillage members and the zinc layer would last at least another 30 to 40 years.

4.2 Interference Survey Along K6Z (Kent TS to Windsor Lauzon TS)

Due to the unusually high corrosion currents measured along Circuit K6Z in Western Region and because of the presence of a Union Gas pipeline within close proximity to the right-of-way, (see Figure 9), an interference survey was conducted at selected tower sites to determine if the pipeline's cathodic protection system was somehow influencing the electrochemical measurements of grillage corrosion. The fact that the high corrosion current measurements did not correlate with the results of shallow visual inspections of the footings, was a contradiction which had to be addressed.

An impressed current cathodic protection system essentially forces a given amount of DC current from groundbed anodes, through a connecting electrolyte (ie soil), and onto an adjacent structure to be protected. Depending on the magnitude of current used, the cathodic areas on the structure will be polarized up to the open circuit potential of the anodic areas. In this manner, corrosion of the structure can be effectively halted. One of the main problems with this technique is the interference with foreign structures which also pick up current from the cathodic protection system. In the case of a transmission line, nearby tower footings could pick up this stray current, forcing their potentials to become more negative and effectively protecting them from corrosion. However, in its attempt to return to a potential low, the electric current can travel from tower to tower, via the connecting skywire, because of the structures inherently lower resistivity compared to earth. Once on the transmission line, the stray current will selectively discharge at certain tower sites, causing accelerated corrosion of the ground line steel. There are several factors which could determine whether a tower will receive or discharge stray currents, however, no fixed rules seem to apply when attempting to predict the pattern of stray current damage. Invariably, personal experience becomes the "rule-of-the-day" when it comes to assessing cathodic protection interference.

With the assistance of Union Gas personnel from Chatham, an interference survey was conducted on rectifiers along the 16 inch Panhandle line between Tilbury and Windsor. The survey was conducted by connecting an automatic circuit interrupter to a rectifier unit of a cathodic protection system and then cycling the current on and off at known intervals. Corrosion potential and corrosion current measurements were made, using the TLIM, at tower sites nearest to the rectifier and pipeline. These measurements were taken during both the on and off cycles, to help determine the level of interference of the cathodic protection system on the tower grillages. A total of three rectifiers were interrupted and these are numbered in the SOCE (Society in Ontario for Controlling Electrolysis) tables as #3, 36 and 92 in the County of Essex.

Rectifier 92 is located in Tilbury North Township and circuit K6Z runs south of this location. Even though Tower 158 is the nearest transmission tower to the rectifier, there was no apparent corrosion potential changes on the footing due to the cycling of current. The E_{corr} value remained stable at -0.713 V and I_{corr} at 3.2 mA. These values are in line with the results of the general survey. The Panhandle pipeline crosses under K6Z between Towers 172 and 173. The influence of the cycling rectifier was observed on the footings of Tower 172 as a drop in potential when the rectifier was cycled on (ie E_{corr} = -0.67 V (off) to -0.65 V (on). This change in E_{corr} suggests that the footings are being depolarized when the rectifier is on, meaning that current is coming off the tower during normal operation of the impressed current protection system. The I_{corr} values on individual footings varied from 2.0 to 3.7 mA, but surprisingly did not change during cycling of the rectifier. No significant corrosion was noted on the footing steel at ground line.

No fluctuation in potentials was noted at Towers 173 (-0.69 V, 3 mA), 206 (-0.64 V, 2.2 mA) or 207 (-0.66 V, 2.5 mA) even though the pipeline was in close proximity to these towers (approximately 10 m).

Rectifier 3 is located in Maidstone Township, south of Belle River Jct and west of Belle River. Tower 256 (-0.6 V, 2.3 mA) and 257 (-0.62 V, 1.4 mA), located east of Belle River, were not influenced by cycling of rectifier 3. This may be due to the river acting as a current sink or barrier. Towers 258, 259 and 260, located just west of Belle River, showed evidence of picking up current during the rectifier's "on" cycle. The E_{corr} values became more negative by 15, 18 and 9 mV respectively. The significant change in corrosion current occurred at Tower 258, where I_{corr} increased from 0.85 mA to 1.03 mA, as the rectifier was cycled on. At Towers 259 and 260, I_{corr} remained stable at 1.25 mA and 0.1 mA respectively. No changes in E_{corr} were noted at Towers 266 and 267, even though the pipeline passes only 10 metres to the north of the transmission line. The pipeline potential was read at a local monitoring point and was noted to fluctuate between -1.5 and -1.23 volts as the rectifier cycled on and off.

Rectifier 36 is located in Sandwich East Township, on the outskirts of Windsor. This is the oldest rectifier station of the three surveyed, and was connected in 1954. Tower 303 is the closest transmission tower to the pipeline and rectifier. Measurements on Leg 1 of this tower revealed that E_{corr} shifted from -0.708 V to -0.742 V and I_{corr} shifted from 1.2 to 1.5 mA as the rectifier cycled off to on. This 34 mV shift in potential was the largest one observed during the survey and indicates that a significant amount of current is being picked up by the tower footings.

Tower 312 showed no effects from cycling of rectifier 36. The tower's E_{corr} value was -0.6 V and I_{corr} = 0.8 mA. Figure 10 is a picture of the ground line grillage steel of Leg 3, showing evidence of moderate corrosion and metal loss.

At Tower 313, the corrosion potential changed from -0.595 to -0.622 V and corrosion current changed from 1.7 to 1.6 mA as the rectifier (located 10 tower spans east of 312) cycled on and off. The magnitude and direction of the change in E_{corr} (Ec_{orr} = 27 mV) indicates that current is being discharged by the footings when cathodic protection for the pipeline is activated. Shallow visual inspections of the footings found evidence of severe corrosion of the original grillage at ground line. Figure 11 shows that only the presence of the outside reinforcing angle has maintained the integrity of Footing 3. The grillage steel 30 cm below ground line is still in reasonable condition, showing evidence of moderate surface corrosion and pitting.

Tower 314, separated by a deep valley and creek from Tower 313, showed no response to cycling of rectifier 36. The E_{corr} value remained steady at -0.61 V and I_{corr} remained at 0.94 mA.

The result of the interference survey is that the Union Gas rectifiers used in the cathodic protection of the Panhandle pipeline between Tilbury and Windsor, are influencing the potentials of some of the towers along Circuit K6Z. The pattern and degree of interference is unfortunately not predictable. The majority of the towers influenced by the rectifiers appear to be picking up current which forces their potentials more electronegative. This phenomenon should be acting to protect the towers from corrosion, which in effect was the result found by the visual inspections reported in Section 3. Some evidence of current discharge was detected at a couple of tower sites, most notably at Tower 313 where severe corrosion of the original grillage steel has taken place.

In general, the corrosion current values measured during the survey tended to be slightly higher during the "on" cycle of the rectifiers. The difference in I_{corr} values between the on and off cycles may have been greater if the de-energizing period had been greater than the 60 seconds used. The dilemma with these I_{corr} values is that they continued to be high, even though the shift in corrosion potentials was in the direction which would indicate decreased corrosion cell activity. A satisfactory explanation for this type of behaviour has not been obtained to date, however, it may be concluded that the presence of the rectifiers is contributing somewhat to the high corrosion currents measured along circuit K6Z.

A quick corrosion survey was conducted on selected towers from circuit K2Z, which parallels circuit K6Z approximately 1 km to the south. This 115-kV transmission line was put into service on July 4, 1940 and is therefore 26 years younger than K6Z. The tower structures along this line are shown in Figure 12. A total of 5 towers were surveyed along this line and the results are tabulated in Table II. The corrosion potentials range from -0.757 to -0.787 volts, which indicates that galvanizing is still protecting the grillage steel. The corrosion currents range from 1.35 to 2.05 mA, which is slightly lower than the range of I_{corr} measured along K6Z in the same area. Whether these corrosion currents are being influenced by nearby rectifiers is as yet unknown. Shallow visual inspections of the grillage footings revealed no evidence of corrosion, as shown in Figure 13.

4.3 Detailed Inspection of Four Oakville Grillages

Following full-scale load tests on Towers 13 and 14 north of Upper Middle Road in Oakville, two footings from each tower were completely excavated and returned to the laboratory for detailed visual inspection. During excavation of each footing, corrosion potential and corrosion current measurements were made at various depths with the TLIM. The objective was to determine how E_{corr} and I_{corr} values changed with depth, as less of the grillage remained in contact with soil. The results of the testing are provided in Table III.

4.3.1 Electrochemical Readings

The corrosion potentials on Footings 13-1, 13-4 and 14-2, tended to decrease with depth, indicating that more corrosion activity had taken place close to the grillage pad than to the ground surface. This conclusion can be justified by the fact that evidence of anaerobic bacterial corrosion was found at depth on previous grillage footings removed from the same transmission line/2/. The most substantial change in E_{corr} occurred on Footing 13-4, where Ec_{orr} of 116 mV was measured across a depth of 4.5 feet (140 cm). In contrast, the changes in E_{corr} measured at Footing 14-4 were insignificant.

Based on the magnitude of corrosion potentials, Footing 14-2 has suffered the least amount of steel corrosion. However, the galvanizing layer has corroded away on all four footings.

No obvious trend appears from the measurements of corrosion current, I_{corr}, with depth. All that can be said is that corrosion activity is low on all four footings and that relatively greater activity is taking place on Footing 14-2.

4.3.2 Inspection of Footing 13-1

During visual inspection of the grillages, several photographs were taken to document the types of corrosion seen. Figures 14 and 15 are photographs taken of Footing 13-1. Figure 14 shows that heavy corrosion products have built up on the grillage below a depth of 1.3 ft. From Figure 15, it may be concluded that the heaviest corrosion product build-up has occurred near the bottom connection of the reinforcing angle, at a depth of 2.6 ft. The corrosion product itself was quite hard and difficult to chip away. The grillage pad members are quite distinctive from the stub angle as there is little build-up of corrosion products and the steel surface is blackened. This may explain the trend of more positive E_{corr} values with depth given in Table III.

4.3.3 Inspection of Footing 13-4

At Tower 13, Leg 4, corrosion products have built-up heavily on the reinforcing angle below a depth of 1.3 ft (40 cm). Above this depth, as shown in Figure 16, minor pitting has developed over the entire surface area of the steel. Below the bottom of the reinforcing angle (2.65 ft), the surface of the original steel is completely blackened, as seen in Figure 17. The bottom of the grillage pad is still in good condition and does not show evidence of major damage by bacterial corrosion. The presence of the blackened surface over most of the underground steel may explain the substantial change in corrosion potentials with depth. The blackened surface is evidence of one of the zinc alloy layers which forms between the base steel and the zinc layer during the galvanizing process.

This footing also exhibited very low corrosion currents at depth, which may be correlated to the lack of pitting corrosion on the grillage steel.

4.3.4 Inspection of Footing 14-4

As shown in Figure 18, corrosion products have built up heavily on the reinforcing angle of Footing 14-4 below a depth of 1.2 ft. Generalized minor pitting has occurred above this depth.

Figure 19 indicates that between the bottom of the reinforcing angle (2.2 ft) and the grillage pad, corrosion products have built up to a lesser degree. General corrosion appears to have occurred across the entire steel surface along this section. Some evidence of the black zinc alloy layer can also be found.

In general, the visual appearance of Footings 14-4 and 13-1 are similar and the electrochemical measurements are also correspondingly similar.

4.3.5 Inspection of Footing 14-2

From Figure 20, it can be seen that corrosion product build-up on the grillage begins at a depth greater than 2 ft (61 cm). Above this depth, only minor surficial corrosion and pitting has occurred on the grillage steel. Below the bottom of the reinforcing angle (2.5 ft), some corrosion product has built up on the original steel and the black zinc-alloy layer is noticeable about 1 ft above the grillage pad (see Figure 21). The most striking corrosion features along this section are the numerous, large, deep pits. Some examples are marked as 1, 2 and 3 in Figure 21. Figure 22 shows Pit #1 with a pit depth gauge indicating a depth of 0.34 inches. The original stub angle thickness was 0.5 inches. Pit depths of 0.31 and 0.4 inches were recorded for Pits 2 and 3 respectively. Numerous smaller pits were also in evidence along the entire section of original steel between 2.5 and 6.3 ft below original ground surface. Corrosion damage has also occurred at the bottom of the grillage pad as shown in Figure 23. The damage takes the form of a 3 cm diameter hole through one of the grillage pad members, as shown close up in Figure 24. The grillage member was bent at this point, however, it is unclear whether the bending occurred during the load testing or during removal of the footing with a backhoe.

Typical thinning of the original ground line steel is shown in Figure 25. The digital micrometer is indicating a remaining thickness of 0.3855 inches compared to the original 0.5 inch thickness. It is worthy to note that the reinforcing angle, placed on the outside of the original stub angle, has not experienced significant metal loss at ground line since it was installed.

The corrosion potential and corrosion current measurements taken at Footing 14-2 were significantly different than for the other footings. The higher corrosion currents may be indicative of corrosion activity associated with the numerous, large pits. The more negative corrosion potentials from Footing 14-2 should indicate that the grillage steel is less corroded than on the other footings. However, the visual evidence, as shown in Figures 21 to 25, does not corroborate this statement.

4.3.6 Main Findings from Oakville Inspection

The main conclusion of this detailed investigation is that surface measurements and observations do not always reflect the condition of buried grillages, especially in the presence of anaerobic bacteria. Notably, corrosion potential readings and the degree of visible corrosion changed dramatically with depth on most of the grillages inspected. The fact that E_{corr} values became more electropositive with depth is an indication that surface potential readings may prove misleading when attempting to evaluate the condition of buried steel. However, in 3 out of the 4 footings examined, the corrosion current readings (I_{corr}) tended to remain the same or decrease with depth. This at least indicates that surface I_{corr} readings provided conservative results in the assessment of underground corrosion. The I_{corr} measurements also provided a check against the E_{corr} measurements since they represented the magnitude of on-going corrosion activity.

The result of the detailed visual inspections was that shallow excavations (1 to 2 ft) around grillage footings in clayey soils, will not provide an indication of the severity of corrosion. Although a significant amount of metal loss has occurred at ground surface on all the grillages, moderate to severe pitting has also occurred at depth, principally due to anaerobic bacteria. Therefore, the I_{corr} measurements at ground surface cannot be correlated to ground level corrosion alone. This discrepancy has already been noted during several corrosion surveys in 1989.

Ultimately, the magnitudes of corrosion currents measured on all four footings were quite low and the overall condition of the grillages, with the reinforcing angles in place, was still good considering that the steel had been buried since 1911.

5.0 DISCUSSIONS

1) During the corrosion surveys, it was noted in a few instances that reinforcing angles were missing altogether. Often it was noted that soil had been allowed to build up above the top of the reinforcing angle, causing accelerated corrosion of the much thinner tower

steel. These situations will have to be investigated on a tower by tower basis and appropriate corrective measures taken to ensure the continued integrity of the tower structure.

2) Galvanic corrosion can develop under several different circumstances. Dissimilar metal surfaces (old and new) and bacteriologic corrosion have been discussed above. Two additional circumstances are also applicable to corrosion of grillage footings: i) dissimilar soils and ii) oxygen concentration. Mixed soil conditions can easily occur within the backfill material of grillage footings. Steel in contact with clay lumps will tend to become anodic to steel in contact with sandy material. Therefore, accelerated metal corrosion could be produced by the use of poor backfill materials or if different materials are placed in layers during construction or upgrading of the grillage footings. Oxygen concentration gradients, also known as differential aeration, are generally found near the ground surface, but they could also be produced by varying degrees of compaction of backfill material during construction or disturbance of the backfill during remedial work. Some evidence of accelerated corrosion was found near the bottom of certain reinforcing angles placed to strengthen the original grillage steel. This may have been caused by the discontinuity in backfill characteristic produced during recompaction of the excavated material.

3) Corrosion potential readings (E_{corr}) can be used as an indicator of the general state of buried steel. Bright steel will have a potential versus a Cu-$CuSO_4$ reference electrode of approximately -0.75 volts, while older, rusted steel will exhibit a potential of -0.40 volts/17/. As shown in Figure 1, the measured E_{corr} value of the corrosion cell actually represents a combination of both the open circuit cathodic and anodic potentials (E_c and E_a). Based on the potentials given above, if new steel is electrically bonded to older steel within an electrolyte, the two materials will become anodic and cathodic respectively and the potential of the total system, with respect to Cu-$CuSO_4$ will lie between -0.75 and -0.4 volts. The potential of an underground steel structure will be a combination of the potentials of the numerous anodic and cathodic sites found on the steel surface. Zinc exhibits a potential versus Cu-$CuSO_4$ of -1.1 volts; therefore, it will behave anodically to new steel and corrode preferentially. Galvanized steel will exhibit a potential between -1.1 and -0.75 volts depending on the amount of zinc left.

Although highly simplistic, the above explanation confirms that as galvanized steel corrodes, the potential of the structure will become more electropositive barring any external interferences. In addition, as the structure polarizes with time, the difference between the anodic and cathodic potentials, also known as the driving potential of the corrosion cell, will tend to decrease causing a reduction in the rate of corrosion.

Figure 26 is a compilation of all of the corrosion potential data collected during the corrosion survey. For each tower line surveyed, the corrosion potentials are represented by an average and a range corresponding to one standard deviation on either side of the mean. The results are plotted in order of increasing in-service date from left to right. This diagram represents the phenomenon discussed above. As grillage footings become progressively older, their corrosion potentials tend to become more electropositive and representative of older, rusted steel. The width of the standard deviation band is representative of the heterogeneity found along individual transmission lines, either in the original quality of the galvanized steel or in the nature of the corrosive environments. Circuit B3/B4 exhibits the widest standard deviation band and happens to be a short line section which rises up the Niagara escarpment from Hamilton and then turns east. Several soil types and corrosive environments can be found along such a route. The potentials of circuit K6Z appear to be higher than they should be, however, this may be due to the interference of the pipeline cathodic protection system discussed in a previous section.

4) Based on results of grillage potential measurements versus depth reported in Sections 1 and 2 in the appendix, and 4.3, corrosion potentials tend to become more electropositive with depth. This indicates that the grillage steel at depth, including the main leg and grillage pad, has suffered more corrosion than the steel closer to the ground surface. Since the soils along these particular transmission lines are predominantly clayey, it can be concluded that anaerobic bacteria have played an important role in the corrosion process at depth. The important conclusion from these tests is that potential measurements taken at ground surface with the TLIM tend to reflect the condition of only near surface steel. In most cases, the Cu-$CuSO_4$ reference electrode is placed within 6 inches (15 cm) of the grillage leg. Consequently, potential readings obtained in this manner will be more representative of the anode/cathode systems closest to the reference half cell.

5) Figure 27 is a compilation of the corrosion current data obtained from all of the corrosion surveys. For each tower line, the average corrosion current and plus/minus one standard deviation are plotted versus in-service date. Based on this graph, there is apparently no clear trend between magnitude of corrosion current and in-service date for these 60 to 80 year-old grillages. Most of the average values fall below 1 mA. This confirms the overall low level of active corrosion taking place on the underground steel.

As shown in Figure 27, the average corrosion currents for circuits K6Z, Q2A/A8TS and A11T/A8W are significantly above those from all other circuits surveyed. The standard deviations associated with these three tower lines are also greater than for most of the other lines. All three lines are of different ages and circuits Q2A and A11T are within the same transmission line corridor between Allanburg W Jct and St. Ann's Jct. It was shown in Section 4.2 that cathodic protection of a pipeline, located near K6Z between Tilbury TS and Windsor Lauzon TS, was having some influence on the grillage potentials. Most grillages appeared to be picking up current which would tend to polarize any cathodic sites to the open circuit potential of anodic sites, effectively reducing corrosion. The reason for the TLIM to give high corrosion currents under these circumstances is yet unclear. Portions of circuits Q2A and A11T may be undergoing similar interferences from stray currents, but this has not been proven to date.

The exponential decay of the corrosion rate of steel with time is a phenomenon which has been well recognized by corrosion engineers both in the laboratory and field settings. The explanations for this phenomenon are quite varied. In the case of straightforward galvanic corrosion of underground steel, a common reaction which occurs at the cathode is the reduction of oxygen to form hydroxyl (OH^-) ions. As oxygen becomes depleted, especially in clayey soils, the process of oxygen reduction diminishes and the corresponding process of iron oxidation must also diminish to maintain electron transfer equilibrium. In addition, the increase in hydroxyl ion concentration at the cathode will cause the local solution pH to increase. This will lead to the precipitation of calcium and magnesium carbonates ($CaCO_3$ and $Mg\ CO_3$) which are common constituents of southern Ontario groundwaters. These solids will precipitate onto the steel structure, further reducing the charge transfer capability of the cathode. The above two processes, plus several others, contribute to what is known as cathodic polarization which effectively reduces corrosion current flow with time. In the case of bacteria-induced corrosion, the gradual depletion of nutrients in the surrounding soils will eventually reduce the rate of corrosion of underground steel. An important point to bring up at this time is that any disturbance of the soil surrounding an underground steel structure, which results in oxygenation of the environment or removal of the protective coating on the steel, will cause depolarization of the anode/cathode systems and renewed corrosion activity.

6) From the examination of several corrosion potential and corrosion current versus tower number graphs, it appears that a relationship between E_{corr} and I_{corr} does exist. As noted in the corrosion survey results, when corrosion currents are relatively high, (ie, greater than 1 mA), the corresponding corrosion potentials tend to be more electronegative. In view of the previous discussion on decreasing corrosion currents with time, it seems reasonable that when underground steel is still galvanized or relatively new, I_{corr} values should be higher. The relationship between I_{corr} and E_{corr} is shown in Figure 28. This graph represents data from approximately 500 towers of different ages. Although no unique relationship is observed, it can be stated that the maximum corrosion current at any given potential, tends to decrease as potentials become more electropositive (ie, as the steel corrodes). The results of corrosion surveys in 1988/89 confirm that corrosion rates decrease with time.

7) Figure 29 represents the results of approximately 370 soil resistivity measurements and corresponding corrosion currents. These results nicely represent the relationship of exponentially decreasing corrosion currents with increasing soil resistivities. Since an increase in soil resistivity is accompanied by an increase in percentage of sand-sized particles, it can be stated that the potential for high corrosion currents decreases in sandy soils. However, the level of corrosion is also dependent on several other factors which are not represented in Figure 29. This is confirmed by the fact that although the relationship is best represented by a power law of the form $Y = aX^b$ where $a = 9.5$ and $b = -1.2$, the correlation coefficient is only equal to 0.651.

8) From a monitoring point of view, the coupling of corrosion currents and corrosion potentials allows for a clearer understanding of the nature and history of corrosion activity at a particular tower site. While the potential reading is a measure of the cumulative effects of corrosion on the grillage steel, the corrosion current indicates the level of active corrosion taking place on the steel.

It must be emphasized that "one-shot" current and potential readings do not, by themselves, give a clear indication of the exact condition of the buried steel. Since the amount of buried steel is large and the potentials are measured versus a $Cu\text{-}CuSO_4$

reference placed only at ground surface, the single corrosion potential measurement only gives a general indication of the condition of the grillage. Unfortunately, the potential reading is not precise enough to reveal the position and intensity of individual corrosion pits which could have completely perforated the grillage leg at one location. Close visual inspection is still the only reliable way of detecting very localized corrosion.

Even though the single corrosion current reading identifies the degree of corrosion activity taking place at the time of measurement, it may not be applicable to other times of the year when activity could increase or decrease. A high corrosion current value also does not automatically imply that the buried steel needs immediate replacement. As discussed previously, relatively newer steel, which is less polarized, could be undergoing galvanic corrosion at a faster rate than older, more corroded steel. High corrosion current values could be used to help determine the need for cathodic protection of certain footings. This could be accomplished by the installation of an appropriate number of sacrificial anodes into the soil surrounding the tower.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The general conclusions from this investigation are listed below.

1) Most of the grillages examined, either through shallow excavations or complete removal, were in surprisingly good condition considering that most of them were between 70 and 80 years old. In general, the most obvious sign of corrosion damage was a thinning of the original stub angle at ground line. This problem was addressed in the past by the installation of a reinforcing angle extending a few feet above and below ground line to strengthen the weakened area. From a corrosion standpoint, the newer steel of the reinforcing angle would have become anodic to the older stub angle and would have corroded preferentially, further protecting the original steel. This conclusion is based on the assumption that no stray currents have affected the tower structure. Although some evidence of surficial corrosion, pitting and build-up of corrosion products was observed on the reinforcing angles, they were found to be generally in good condition. This underscores the relative slowness of the corrosion process which has affected the grillage footings.

The prevalence of electric trains during the first half of the century caused a significant problem of stray DC currents on nearby structures. This may have lead to the accelerated corrosion of grillage steel at ground line which in turn lead to the installation of the reinforcing angles. The subsequent reduction in electric train usage would have lowered the corrosion rate of the grillage steel.

2) Grillages founded in clayey soils, such as found in the Oakville area, have experienced significant corrosion at depth due to the presence of sulphate-reducing bacteria. As the bacteria gradually exhaust their nutrients, the corrosion process tends to decrease until a new supply of nutrients is input to the system such as via disturbance of the surrounding soil. This type of bacteria-induced corrosion tends to occur at depth and may not be readily detectable using the TLIM at ground surface or by shallow excavation.

3) The Tower Leg Integrity Monitor (TLIM) was used to measure corrosion potential (E_{corr}) and corrosion current (I_{corr}) of every footing at selected tower sites. The equipment proved to be rugged, easy to use and reliable. The measurement of corrosion current takes only slightly longer than if corrosion potentials alone are read. Some minor manipulation of the original data is required to obtain I_{corr}, but this can be done in the field with a pocket calculator. As a result, this TLIM could be easily used by field personnel with only a minor amount of training.

4) By providing a measurement of corrosion current, the TLIM has indicated that at least at ground surface, the degree of corrosion on the grillage leg is quite low. The average corrosion current from all surveys conducted in 1988/89 is approximately 1 mA. However, the most common I_{corr} value, statistically referred to as the mode of the data set, is equal to 0.3 mA. This implies that the distribution of all corrosion currents is skewed towards higher I_{corr} values.

5) Footing potentials from towers put into service in 1910 range from -0.4 to -0.6 volts. This indicates that the original protective layer of zinc has corroded away and that the grillage steel on most of the footings has also corroded to some degree. Younger towers exhibit footing potentials which are progressively more electronegative.

6) A partial correlation exists between E_{corr} and I_{corr} measurements. Under normal conditions, high corrosion current readings appear to be associated with more electronegative footing potentials, ie, relatively younger towers may exhibit higher corrosion rates.

7) An inverse power law relationship exists between soil electrical resistivity and corrosion current. As soil resistivity increases, the tendency for high corrosion currents decreases.

The recommendations arising from the corrosion surveys are:

1) The high corrosion currents recorded along circuit K6Z, Q2A and A11T, should be further investigated to determine their cause (ie, either natural galvanic corrosion or effects of stray DC currents from nearby cathodic protection systems).

2) It is extremely difficult to assess the severity of underground corrosion of buried grillages based on one-time corrosion potential and corrosion current readings. Corrosion surveys conducted at reasonably regular intervals would help to determine, qualitatively, the rate of decay of buried steel. Using this time-dependent data, an assessment of whether corrosion activity is accelerating, staying the same or decreasing, could be made. This type of data, and not just single values in time, could help target problem areas for increased surveillance or refurbishment. Regularly scheduled surveys are even more important now than in the past, since many of the 80-year-old grillages are entering the next phase of their working lifetime.

3) At present, use of the TLIM requires that a $Cu\text{-}CuSO_4$ reference electrode be placed at ground surface and that a short auxiliary electrode be pushed into the ground near the grillage leg. This type of configuration tends to provide E_{corr} and I_{corr} values which are more representative of shallow grillage steel. Since differential aeration is one of the main causes of corrosion and tends to occur primarily near ground surface, the present configuration does provide satisfactory results. However, as noted in the detailed excavations and visual inspections, anaerobic bacteria have promoted significant pitting corrosion at a depth of several feet below ground surface in southern Ontario. A possible modification of the present TLIM set-up would be to insert the reference electrode to greater depths into the soil using a properly designed probe. The auxiliary electrode could also be made longer and pushed deeper into the ground following successive corrosion

current readings. These simple modifications would make routine corrosion surveys more time consuming, but if only applied to specific tower sites, they could greatly enhance the understanding of grillage corrosion patterns without requiring detailed excavations.

4) Continuous monitoring of corrosion potentials and corrosion currents at selected tower sites could be accomplished by using remote data acquisition techniques. This type of research program would enhance our understanding of the relationship between E_{corr} and I_{corr} to changing environmental conditions such as precipitation, temperature and stray currents. The benefit of such a program would be to determine the importance of these outside factors in underground corrosion and possibly to identify the optimum time of year, if any, for conducting corrosion surveys.

5) The applicability of the TLIM could be increased by attempting to evaluate corrosion activity on other buried structures such as anchor rods, reinforced concrete footings, sacrificial anodes and more. In some of these cases, the measured corrosion current could be applied over a smaller and more regular surface area, which would allow the calculation of more realistic metal consumption rates.

6) Finally, the factors which contribute to underground corrosion should be well understood and taken into account during any program of footing rehabilitation. The disturbance of the backfill material followed by poor compaction will lead to increased oxygenation and differential aeration in the soils surrounding the grillage. Poor quality backfills and/or backfill materials which are not compatible with the surrounding native soils may lead to the formation of large anodic/cathodic areas on the steel adjacent to the backfill/soil boundaries. The disturbance of the backfill may also provide dormant anaerobic bacteria with new sources of nutrients. The above factors are only some of the processes which could lead to a renewal of corrosion activity and accelerated deterioration of the grillage footings. These factors must be assessed before and during any rehabilitation program.

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TABLE I
TRANSMISSION LINES SURVEYED DURING 1988/89

CIRCUIT	LINE SECTION	REGION	LINE KM'S	I/S DATE	AVG Ecorr	AVG Icorr
					V	mA
B5G/B6G	HARPER'S JCT x GUELPH CEDAR TS	CENTRAL	30.32	10.10.01	-0.484	0.3
D7G/D9G	GUELPH CEDAR TS x FREEPORT JCT	CENTRAL	23.74	10.10.01	-0.531	0.42
B12/B13	DUNDAS TS x BRANT TS	CENTRAL	36.45	10.11.01	-0.569	0.87
B2W/B8W	BRANT TS x WOODSTOCK TS	WESTERN	35.13	10.11.01	-0.57	0.88
W7W/W8W	WOODSTOCK TS x BUCHANAN TS	WESTERN	45.10	10.12.01	-0.558	0.51
D8S/D10H	LEONG JCT x ST.MARYS TS	CENTRAL	56.62	10.12.01	-0.55	0.85
L7S	ST.MARYS TS x DEVIZES JCT	WESTERN	14.92	10.12.01	-0.549	0.85
K6Z	KENT TS x WINDSOR LAUZON TS	WESTERN	67.42	14.08.01	-0.654	2.14
B3/B4	DUNDAS TS x GLANFORD JCT	CENTRAL	13.21	15.02.01	-0.639	0.96
Q2A/Q8TS	ALLANBURG W JCT x ROSEDENE JCT	WESTERN	14.65	10.10.01	-0.636	1.94
	ROSEDENE JCT x ST.ANNS JCT	WESTERN	11.18	15.12.19		
K7B/K8B	TRAFALGAR JCT x NELSON JCT	CENTRAL	22.91	22.07.01	-0.692	0.99
A11T/A8W	ALLANBURG W JCT x ST.ANNS JCT	WESTERN	25.85	29.06.09	-0.77	1.87
M31A	OTTAWA HAWTHORNE TS x MERIVALE TS	EASTERN	12.02	32.10.20	-0.745	0.55
*	HALTON JCT x "OLD" COOKSVILLE TS "B"	CENTRAL		11.03.01	-0.541	0.89
	(OAKVILLE LINE)					

*surveyed in 1988

TABLE II

Circuit: K2Z
Section: Kent Jct x Woodslee Jct (Western Region)
In-service date: 40.07.04

TOWER #	Ecorr (-V)	Icorr (mA)
456	0.787	1.48
457	0.777	1.82
461	0.772	1.35
466	0.757	2.05
470	0.763	n/a

TABLE III

Section: Halton Jct x "Old" Cooksville TS "B"

TOWER: 13
LEG: 1

Depth (cm)	Depth (ft)	Ecorr (-V)	Icorr (mA)
0	0	0.553	0.08
71	2.3	0.551	0.39
142	4.6	0.499	0.32
206	6.7	-	-

TOWER: 13
LEG: 4

Depth (cm)	Depth (ft)	Ecorr (-V)	Icorr (mA)
0	0	0.57	0.33
91	3	0.524	0.17
137	4.5	0.454	0.19
208	6.8	-	-

TOWER: 14
LEG: 2

Depth (cm)	Depth (ft)	Ecorr (-V)	Icorr (mA)
0	0	0.638	0.63
61	2	0.63	0.58
122	4	0.607	0.85
208	6.8	-	-

TOWER: 14
LEG: 4

Depth (cm)	Depth (ft)	Ecorr (-V)	Icorr (mA)
0	0	0.555	0.39
66	2.1	0.548	0.34
137	4.5	0.562	0.24
194	6.4	-	-

N.B. Last depth value corresponds to the bottom of the grillage

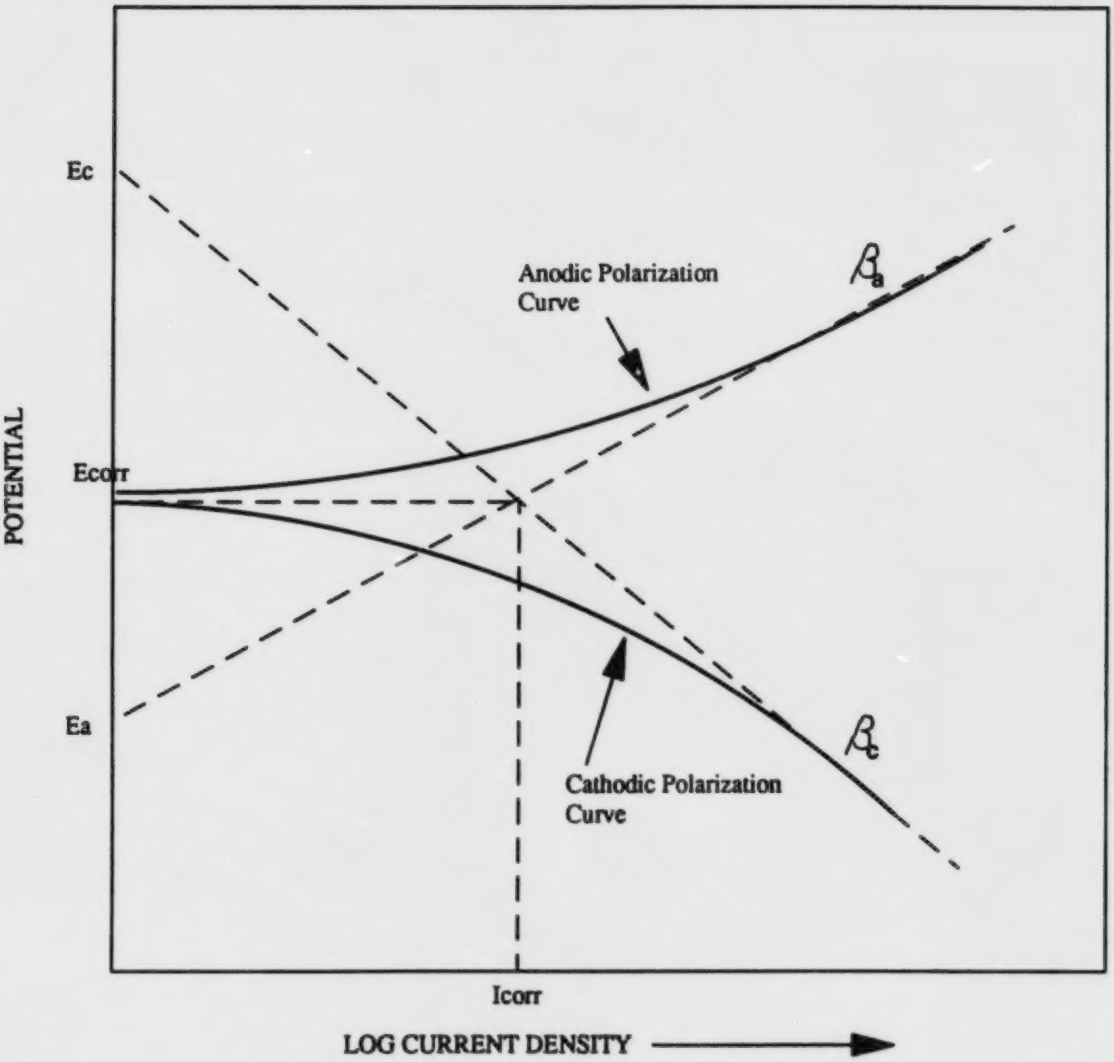

Ec
Anodic Polarization Curve
β_a
POTENTIAL
Ecorr
Ea
β_c
Cathodic Polarization Curve
Icorr
LOG CURRENT DENSITY

FIGURE 1
Example Polarization Curves

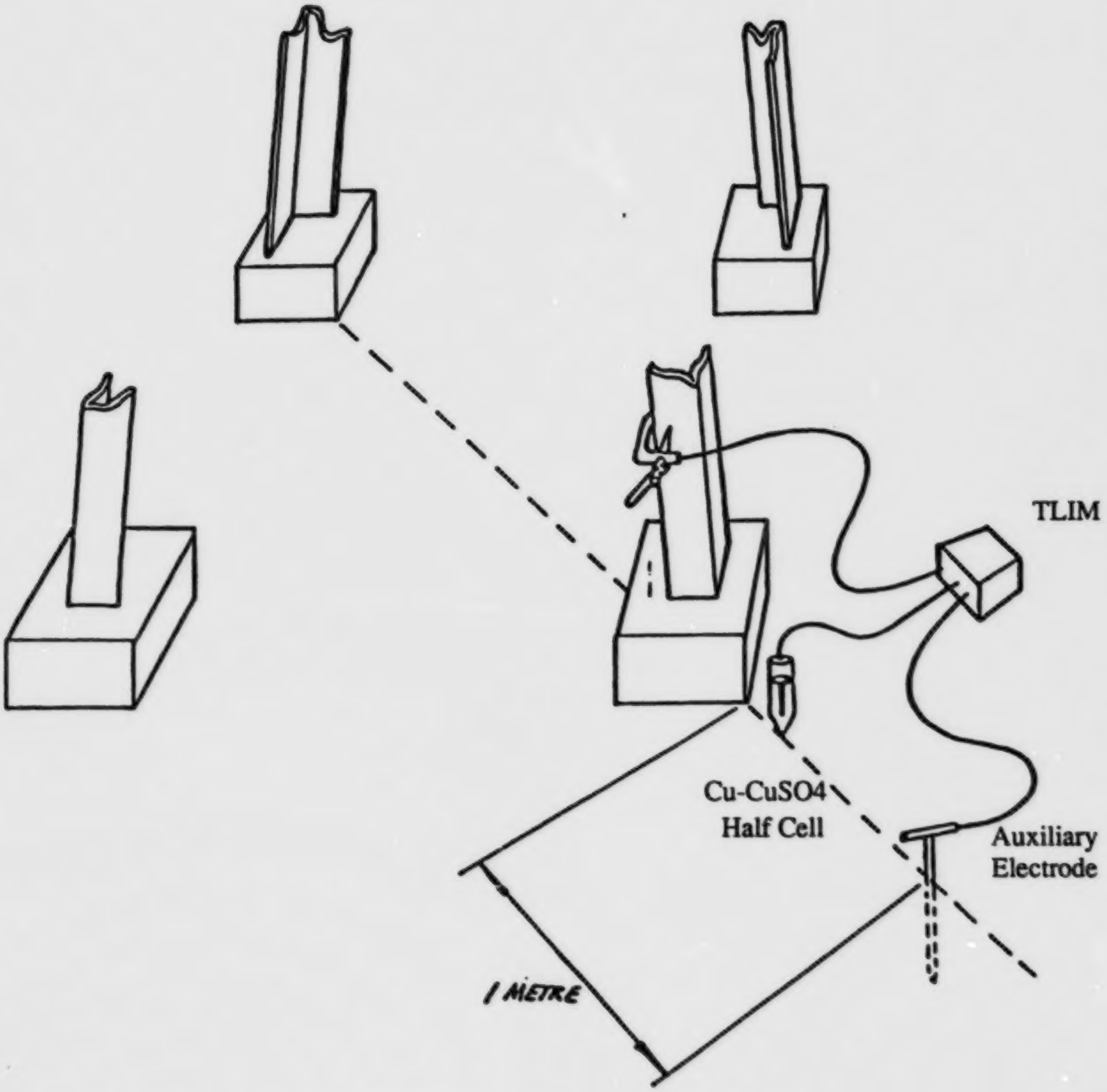

TLIM
Cu-CuSO4 Half Cell
Auxiliary Electrode
1 METRE

FIGURE 2
TLIM Field Layout (repeated at each footing)

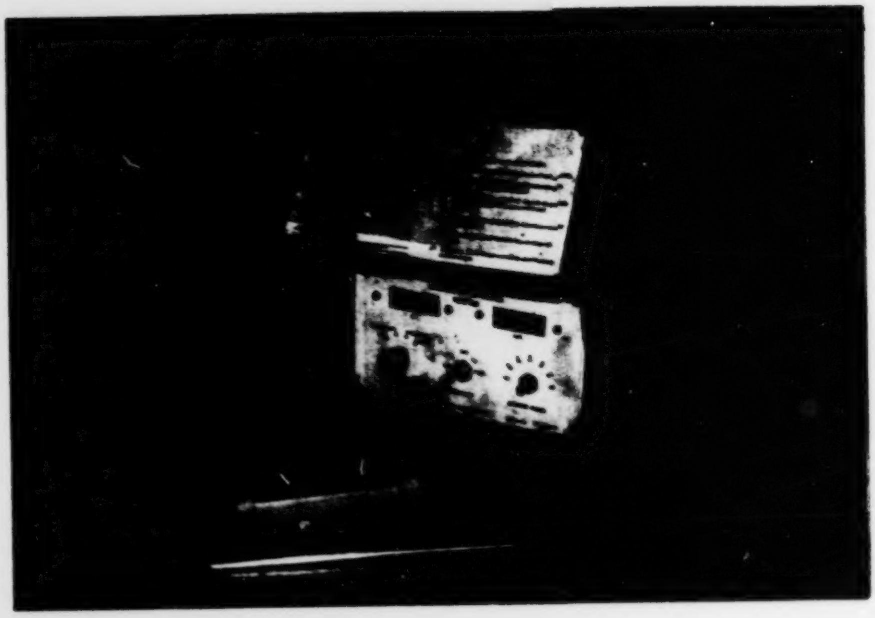


FIGURE 3

TOWER LEG INTEGRITY MONITOR

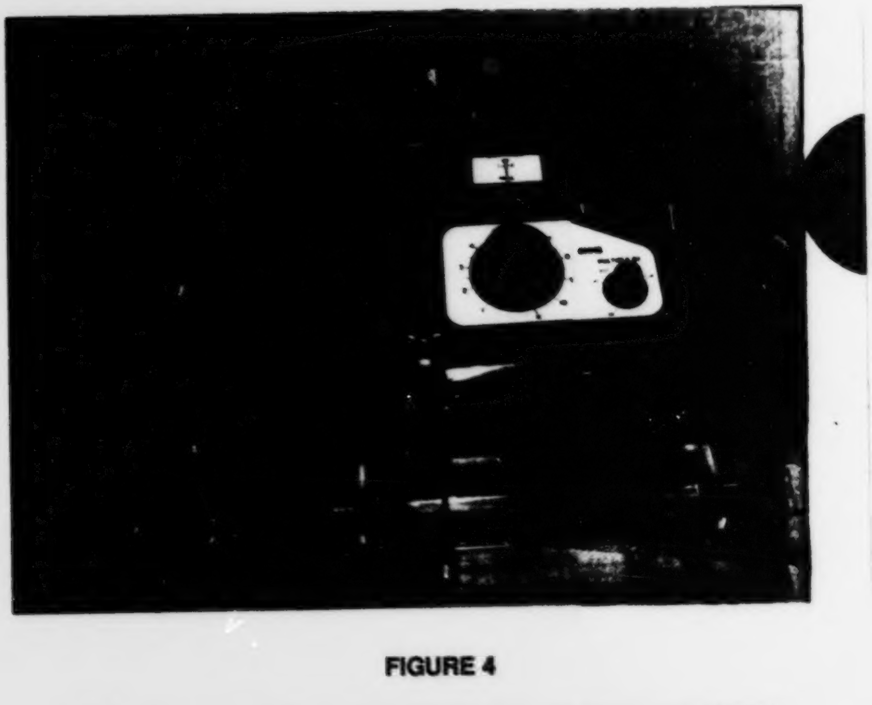


FIGURE 4

MILLER SOIL BOX AND NILSSON SOIL RESISTANCE METER

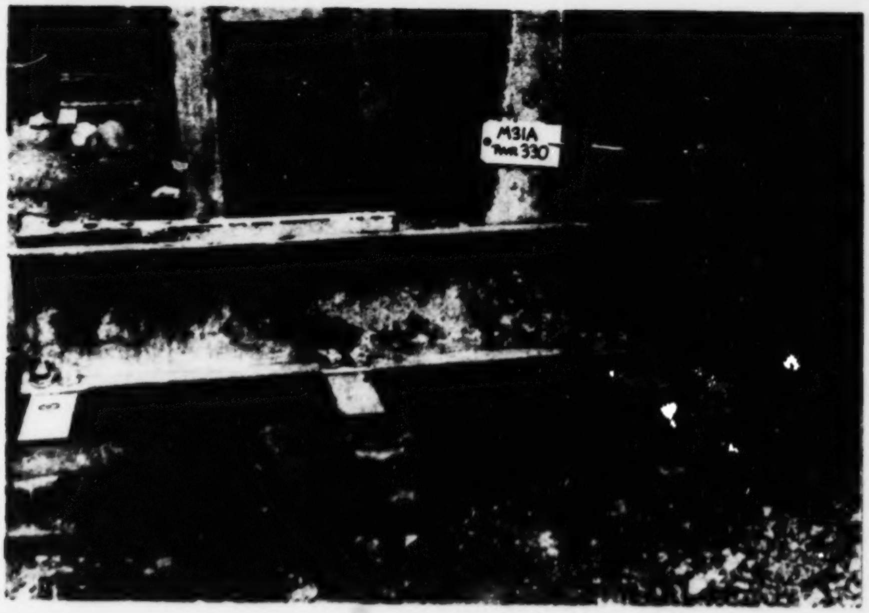

M31A
Twr 330

FIGURE 5

CIRCUIT M31A - TOWER 330

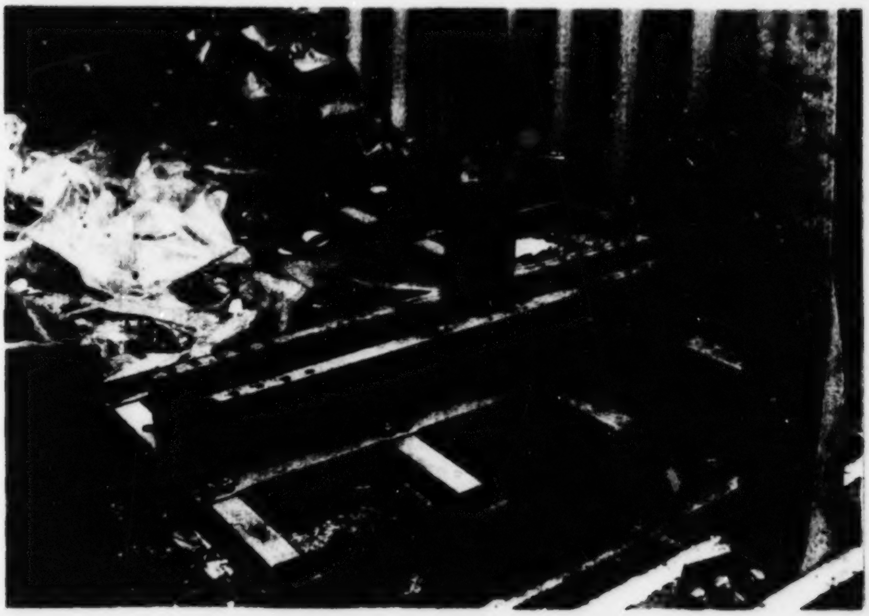


FIGURE 6

CIRCUIT M31A - TOWER 331

FIGURE 7

CIRCUIT M31A - TOWER 335

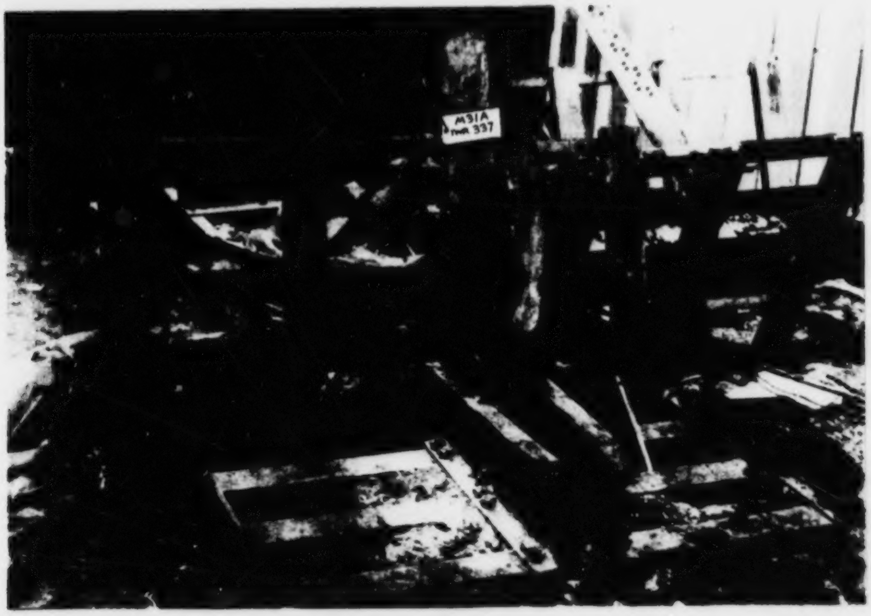


FIGURE 8

CIRCUIT M31A - TOWER 337

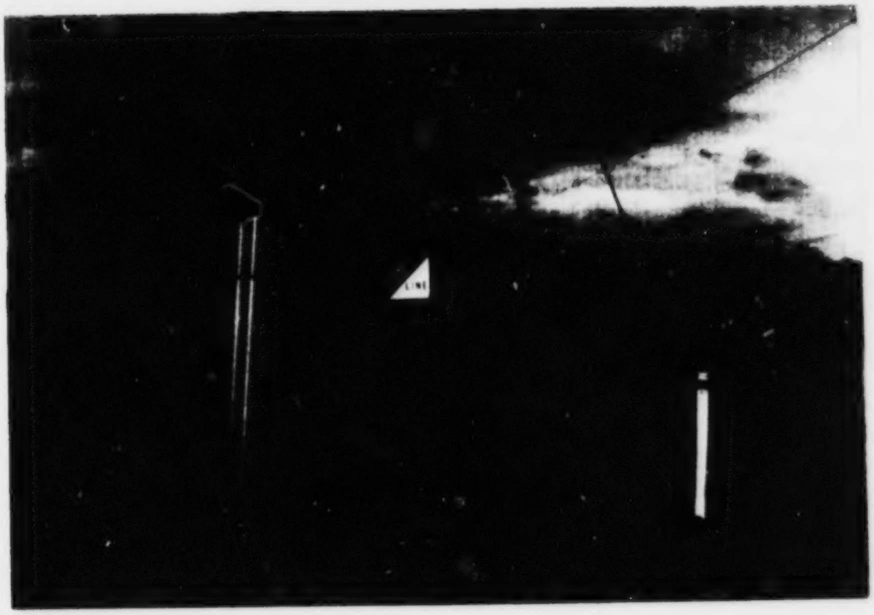


FIGURE 9

CIRCUIT K6Z - WEST OF BELLE RIVER JCT

FIGURE 10

CIRCUIT K6Z - TOWER 312

FIGURE 11

CIRCUIT K6Z - TOWER 313

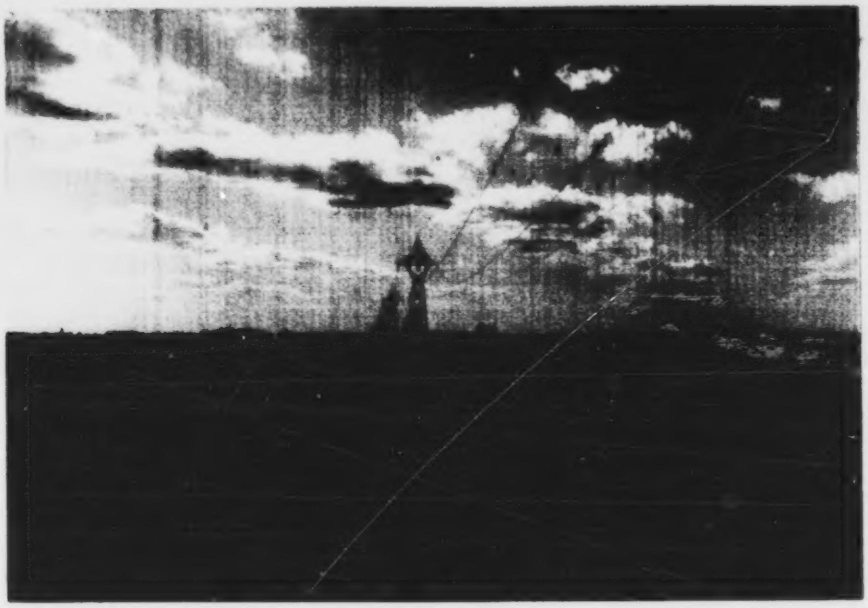


FIGURE 12

CIRCUIT K2Z - LOOKING EAST

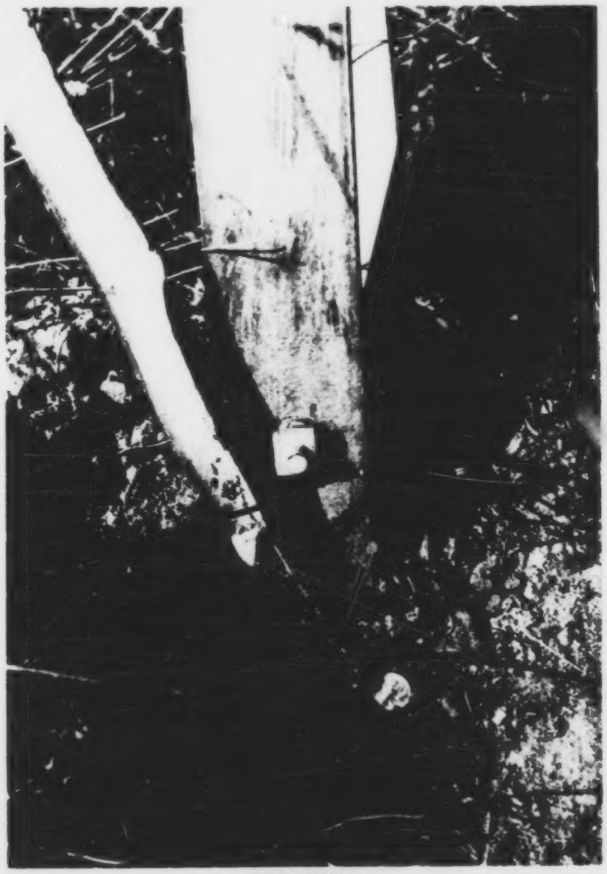


FIGURE 13

CIRCUIT K2Z - TYPICAL APPEARANCE OF FOOTING AT GROUNDLINE

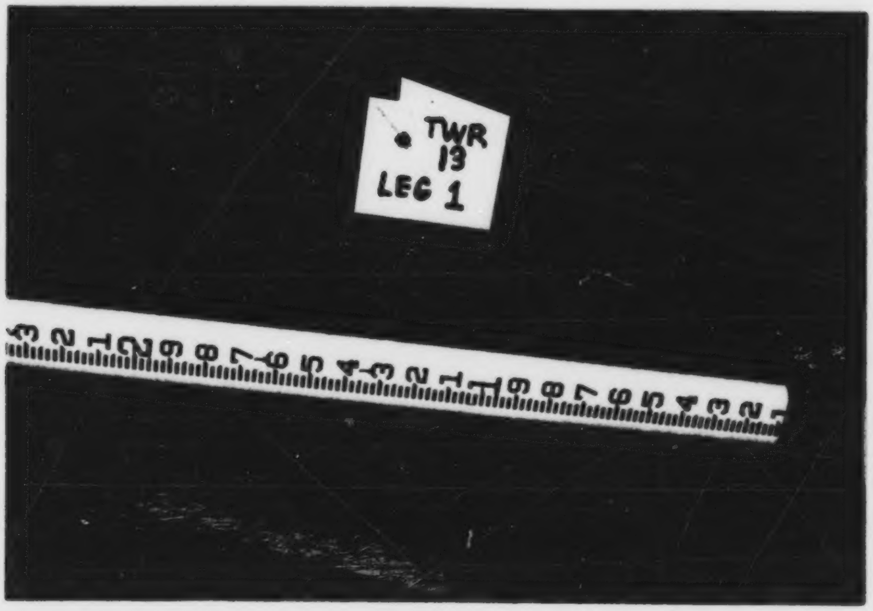


FIGURE 14

OAKVILLE - TOWER 13, LEG 1 (0 - 2.3 ft)

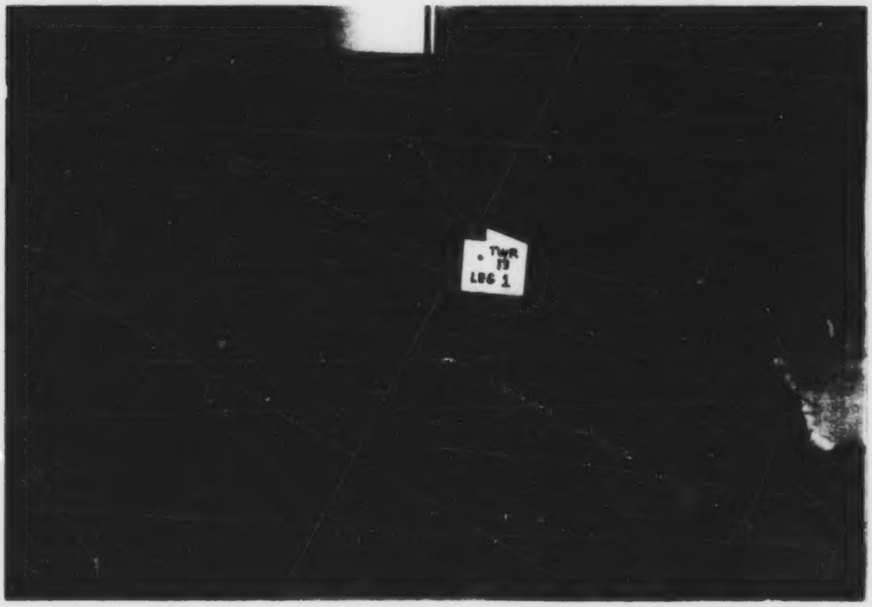


FIGURE 15

OAKVILLE - TOWER 13, LEG 1

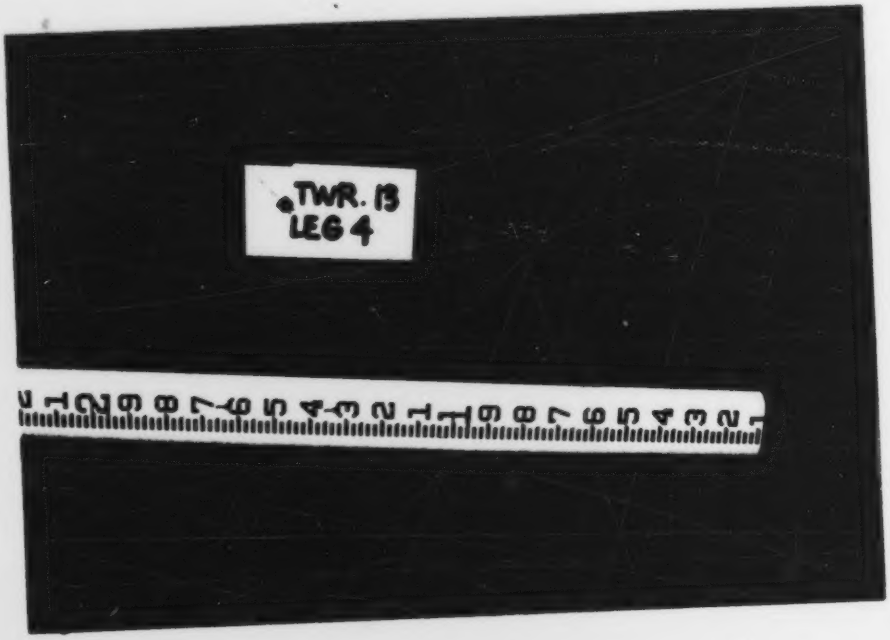


FIGURE 16

OAKVILLE - TOWER 13, LEG 4 (0 - 2.2 ft)

FIGURE 17

OAKVILLE - TOWER 13, LEG 4 (3.9 - 6.1 ft)

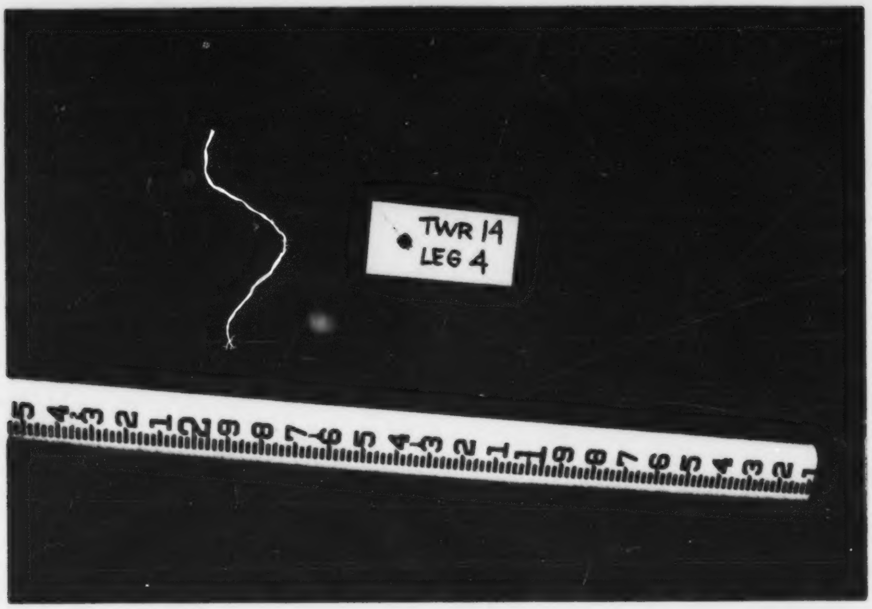


FIGURE 18

OAKVILLE - TOWER 14, LEG 4 (0 - 2.5 ft)

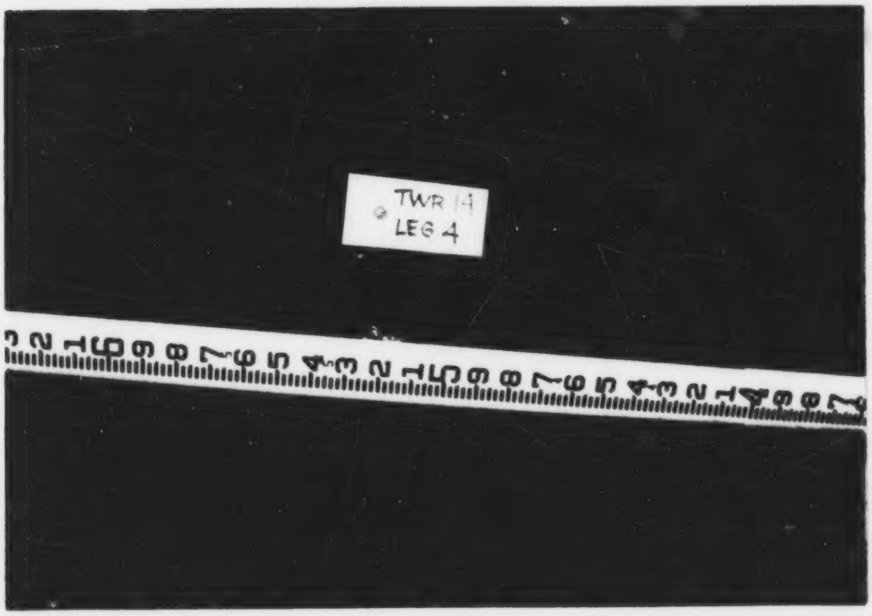


FIGURE 19

OAKVILLE - TOWER 14, LEG 4 (3.6 - 6.3 ft)

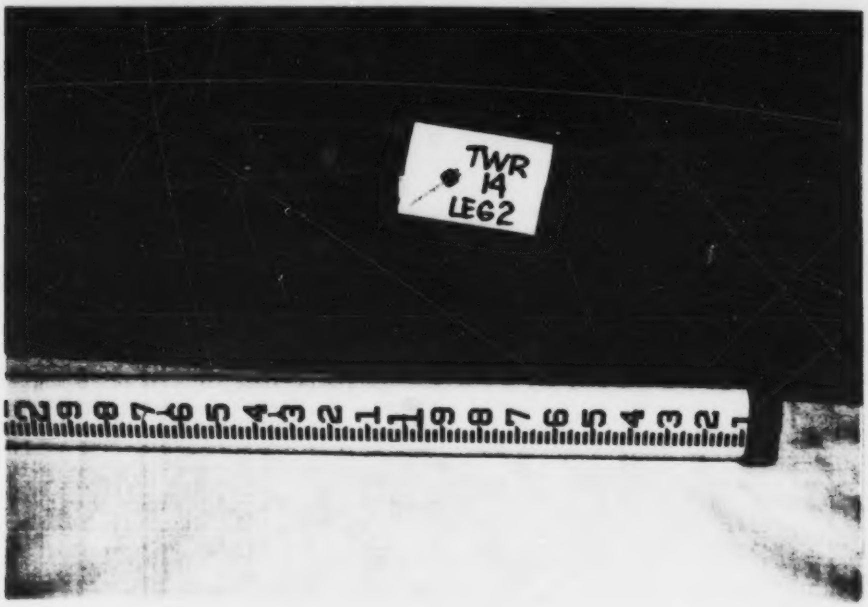


FIGURE 20

OAKVILLE - TOWER 14, LEG 2 (0 - 2.1 ft)

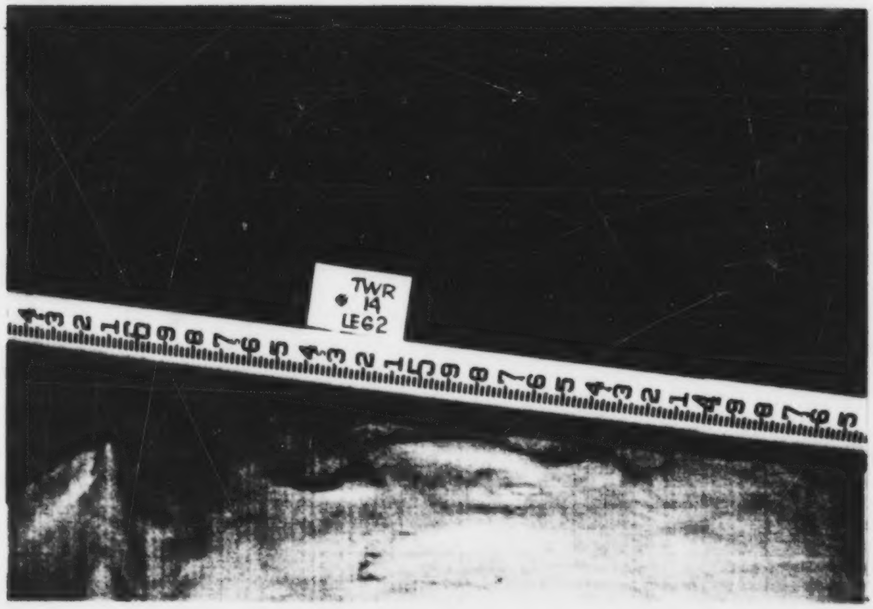


FIGURE 21

OAKVILLE - TOWER 14, LEG 2 (3.5 - 6.5 ft)

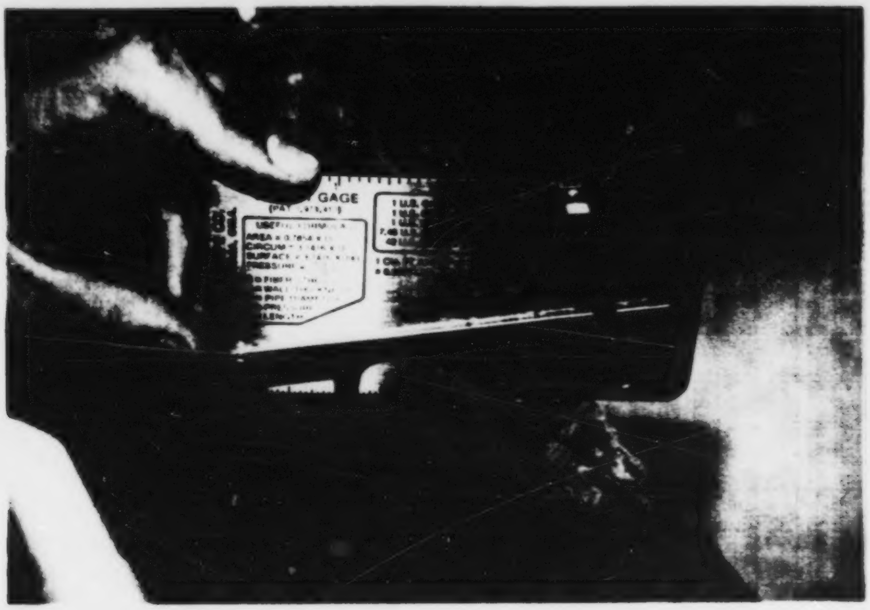


FIGURE 22

OAKVILLE - TOWER 14, LEG 2

FIGURE 23

OAKVILLE - TOWER 14, LEG 2

FIGURE 24

OAKVILLE - TOWER 14, LEG 2 (BOTTOM OF GRILLAGE)

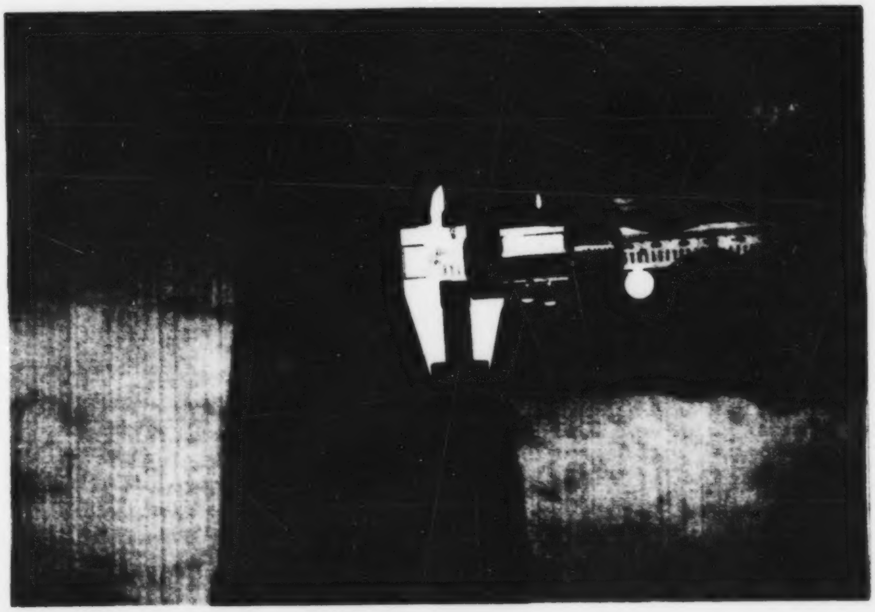
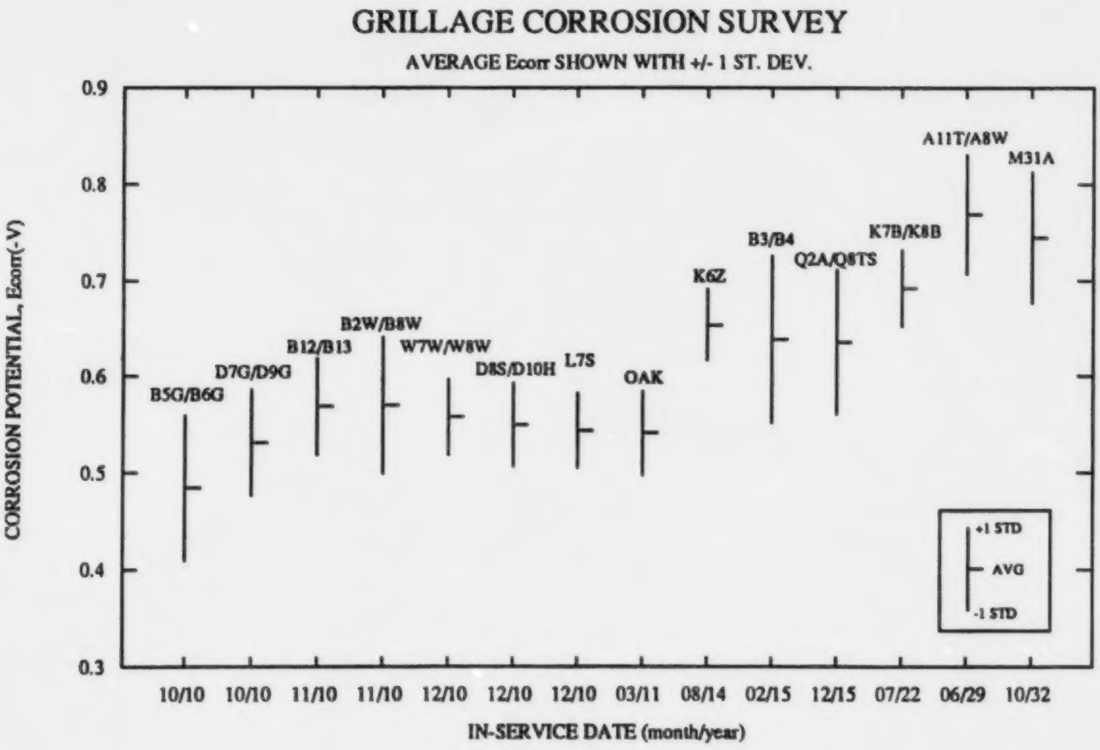


FIGURE 25

OAKVILLE - TOWER 14, LEG 2
ORIGINAL ANGLE THICKNESS AT GROUND LINE = 0.3855 In


GRILLAGE CORROSION SURVEY

AVERAGE Ecorr SHOWN WITH +/- 1 ST. DEV.

FIGURE 26

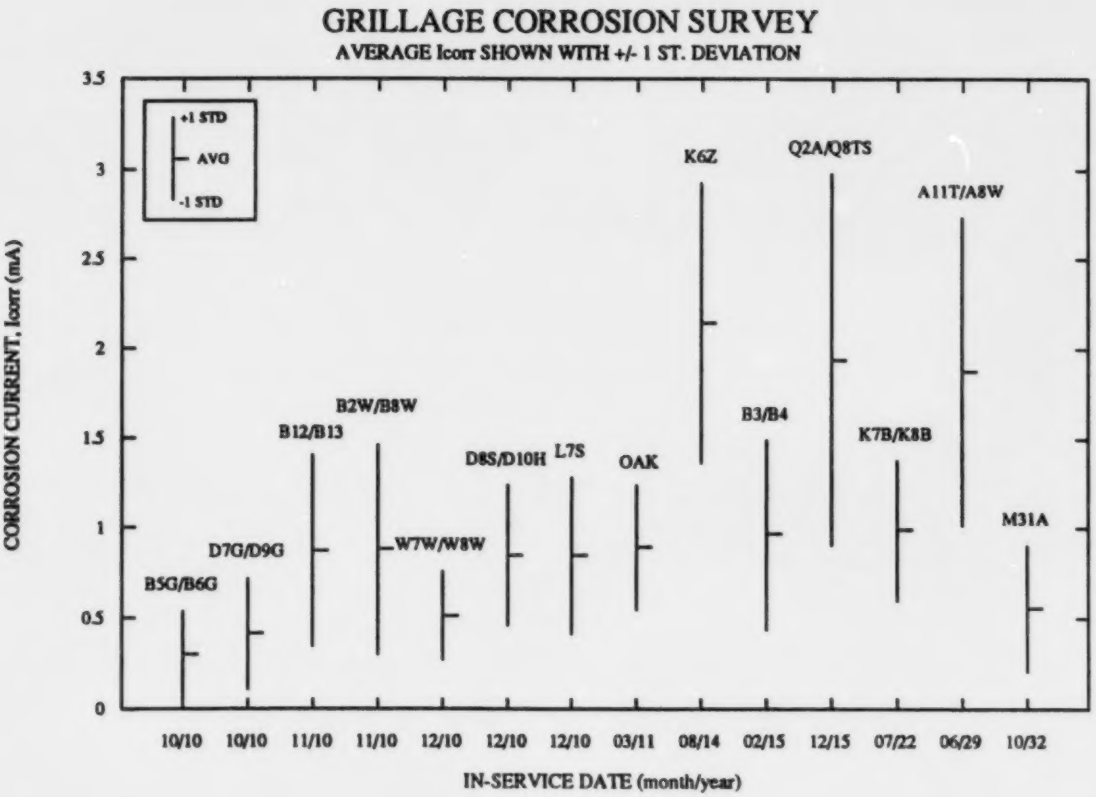

GRILLAGE CORROSION SURVEY
AVERAGE Icorr SHOWN WITH +/- 1 ST. DEVIATION
+1 STD
AVG
-1 STD
CORROSION CURRENT, Icorr (mA)
3.5
3
2.5
2
1.5
1
0.5
0
B5G/B6G
D7G/D9G
B12/B13
B2W/B8W
W7W/W8W
D8S/D10H
L7S
OAK
K6Z
B3/B4
Q2A/Q8TS
K7B/K8B
A11T/A8W
M31A
10/10
10/10
11/10
11/10
12/10
12/10
12/10
03/11
08/14
02/15
12/15
07/22
06/29
10/32
IN-SERVICE DATE (month/year)

FIGURE 27

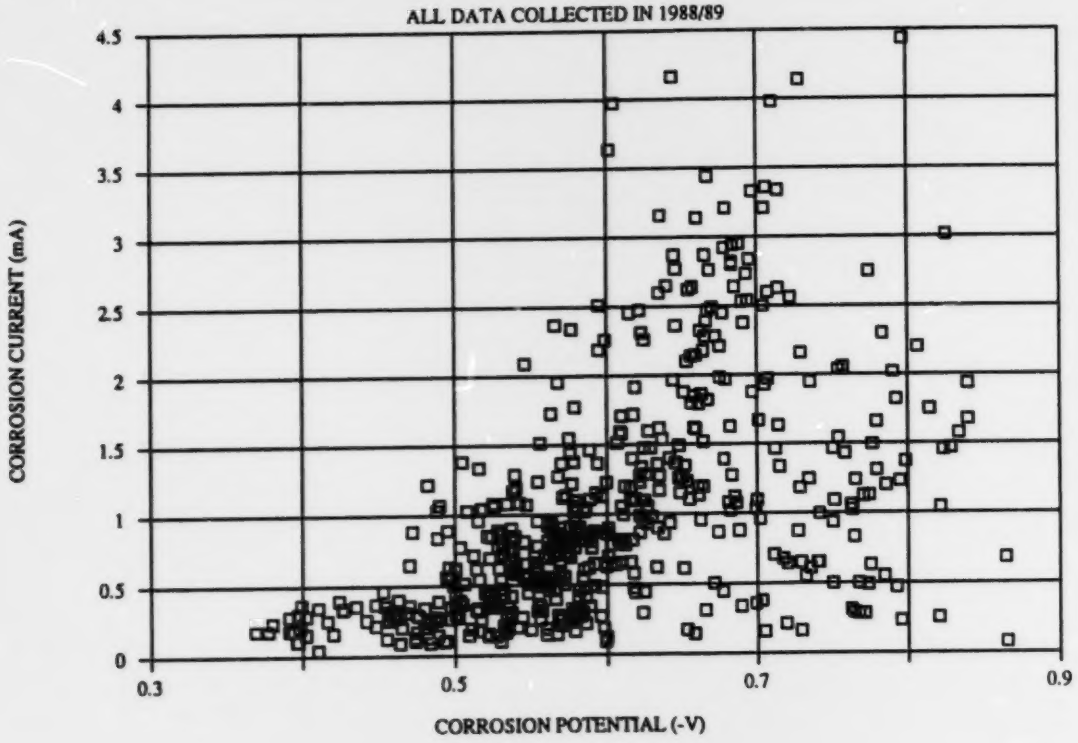

ALL DATA COLLECTED IN 1988/89
CORROSION CURRENT (mA)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.3
0.5
0.7
0.9
CORROSION POTENTIAL (-V)

FIGURE 28

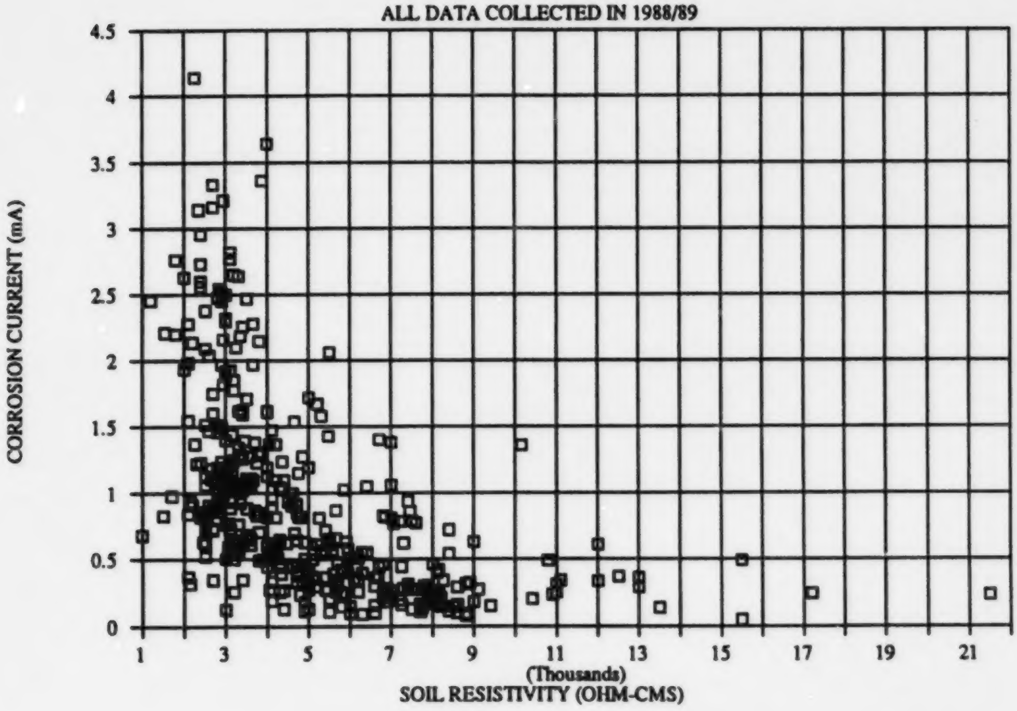

ALL DATA COLLECTED IN 1988/89
CORROSION CURRENT (mA)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1
3
5
7
9
11
13
15
17
19
21
(Thousands)
SOIL RESISTIVITY (OHM-CMS)

FIGURE 29

APPENDIX

Summary of 1989 Grillage Corrosion Survey by Tower Line

1.0 Harper's Jct to Guelph Cedar TS (B5G/B6G)

Circuit B5G/B6G, which extends from Harper's Jct to Guelph Cedar TS is a 115-kV transmission line covering a distance of 30.32 kms and consisting of 188 steel towers. The in-service date was October 1, 1910. A total of 49 towers were inspected along this line, representing 26% of the steel structures present. Results of the survey are tabulated in Table A1 and selected results are plotted in Figures A1 to A3. Based on the corrosion potential measurements, ranging from -0.36 to -0.66 volts, the galvanizing layer has corroded away on most of the grillages and steel corrosion has also taken place, most notably between towers 125 and 155. Corrosion currents, represented in Figure A2, range from 0.1 to 0.5 mA.

I_{corr}-values from Towers 50, 97 and 98 are significantly above background and should be inspected according to Cormon's TLIM manual. These currents are quite low especially if distributed over the entire grillage surface area.

Soil resistivity measurements obtained from collected soil samples are plotted in Figure A3. On average, the resistivity values range from 5,000 to 9,000 ohm/cms which would classify the soils as moderately corrosive. Some anomalously low soil resistivities were measured at Towers 50, 54, 120, 175 and 210. These resistivities are between 2,000 and 4,100 ohm-cms and tend to correlate with corrosion current peaks in Figure 5b.

A field inspection of selected tower sites was undertaken which consisted of excavating around one grillage footing per tower. Along with a visual inspection of the steel, corrosion potential readings were also taken as the excavation progressed. This helped assess any changes in steel characteristics with depth. One footing at Towers 50, 96, 140 and 145 was inspected.

At Tower 50, Leg 2, the leg-to-soil potential changed from -0.68 volts at the frozen ground surface to -0.66 volts at a depth of 2 metres, ie at the grillage pad. Visual inspection of the grillage leg concluded the following:

- An offset reinforcing angle "Mark 1", as per Drawing TD08455C", had been placed on the original leg angle at ground line to protect against metal loss due to corrosion. The dimensions of the reinforcing angle are 4" x 4" x 1/2" thick and approximately 48" (1.22 m) along.

- The most serious corrosion has taken place just below ground line where the original angle thickness has decreased by 28%. The addition of the reinforcing angle has helped to maintain the structural integrity of the footing.

- Pitting corrosion has taken place on the outside surface of the reinforcing angle as shown in Figure A4.

- Below the estimated depth of the water table, the original grillage steel was black and completely smooth with only some minor scalloping and pitting indicative of microbiologically induced corrosion (see Figure A5).

Tower 97 could not be excavated safely because of its location in a swampy area. Tower 96 was inspected instead and the following observations were made:

- Tower 96 was still difficult to inspect because of water running into the excavation as shown in Figure A6.

- Leg-to-soil potential at a depth of 1 m was -0.59 volts changing to -0.47 volts at a depth of 1.68 m. This indicates that more severe corrosion may be occurring at the grillage pad.

- Large, smooth pitting indicative of bacterial corrosion was present on and below the reinforcing angle and the remainder of the leg steel was black and smooth as shown in Figure A7.

The following observations were made at Tower 140:

- The leg-to-soil potential was -0.384 volts at a depth of 1 m changing to -0.369 volts at 2 m.

- The thickness of the original angle at ground line has reduced by 50%.

- Extensive surface corrosion and pitting has occurred on the reinforcing angle to a depth of 1 m, as shown in Figure A8.

- The soil in the vicinity of the tower consists of a gravelly sand with large boulders and low moisture content. This would imply a high soil resistivity and correspondingly low corrosion activity. Good aeration of the soil at ground line may have promoted the corrosion activity.

- Some localized pitting was observed below a depth of 1.5 m.

The following observations were made at Tower 145:

- The leg-to-soil potential was equal to -0.381 volts at a depth of 0.75 m, changing to -0.354 volts at 1.67 m.

- The soil type is a gravelly sand as at Tower 140.

- Extensive surface corrosion and pitting has occurred on and above the reinforcing plate since the soil was built-up around the original tower steel (see Figure A9).

- Some minor surface pitting has occurred below a depth of 1.67 m.

Following the inspection of four grillage footings from four tower sites along Circuit B5G/B6G, it may be concluded that these 80-year-old footings are still in good condition especially since the reinforcing angles were installed. The steel grillage foundations were reinforced, apparently in the 1930's, to protect the ground line steel from further corrosion damage caused by DC currents from electric trains. The validity of the E_{corr} and I_{corr} measurements could not be determined from the footings inspected since, in all four cases, the levels of visible corrosion were approximately the same. The most significant difference between Towers 50 and 140 is their environment: i) the grillages at Tower 50 are partially submerged below the water table and the soil is very clayey, ii) the grillages at Tower 140 are above the water table and the soil is a gravelly sand.

2.0 Guelph Cedar TS x Freeport Jct (D7G/D9G)

Circuit D7G/D9G, from Guelph Cedar TS to Freeport Jct, is a 115-kV transmission line covering a total distance of 23.74 kms and consisting of 165 steel tower structures. The in-service date was October 1, 1910. A total of 24 towers were inspected along this line representing 14% of the steel structures present. Results of the survey are tabulated in Table A2 and selected results are plotted in Figures A10 to A12.

Since the corrosion potential measurements plotted in Figure A10 range from -0.4 to -0.63 volts and average approximately -0.53 volts, the zinc galvanizing layer has corroded away and steel corrosion has occurred, most notably between Towers 30 to 80. The relatively higher potentials associated with Towers 119 and 144 (E_{corr} = -0.618 and -0.63 volts respectively) are due to the presence of newer steel used to raise the towers in the past.

The corrosion currents, plotted in Figures A11 are slightly higher in magnitude than those measured along B5G/B6G. The values range from 0.1 to 0.7 mA, averaging 0.42 mA. The readings from Towers 24 and 142 are outside of this range and are equal to 1.37 and 0.98 mA respectively. Based on the survey procedure outlined in the TLIM manual, these two towers should be inspected.

The soil resistivity measurements are plotted in Figure A12. In general, the values range from 4,000 to 9,000 ohm-cms which identifies the soil types along this tower line as moderately corrosive to corrosive. The exceptions are the soils found at towers 10, 111 and 142 which are corrosive to non-corrosive. There appears to be a slight relationship between soil resistivity and corrosion currents along this tower line, since moderately higher currents (0.7 mA) tend to correlate with soil resistivities which are 4,000 ohm-cms or less. This relationship could not be further developed since several towers numbered between 90 and 110 appeared to have concrete footings. These would have different corroding characteristics than most of the grillage-type footings.

Full visual inspections were conducted on the following towers: #24, 45, 80 and 142. Based on a high I_{corr} measurement, Tower 25 should have been inspected. But since Tower 25 is a turning tower, it was decided to leave its grillage footings intact and inspect adjacent Tower 24 instead.

The corrosion potentials measured at Tower 24 changed from -0.6 volts at a depth of 0.60 m to a value of -0.58 volts at 1.52 m. In general, the steel was in good condition with only some slight surface corrosion and pitting, and no evidence of any metal loss.

Corrosion potentials measured at Tower 45 changed from -0.55 volts at a depth of 0.6 m to a value of -0.5 volts at 1.83 m. Some surface corrosion and pitting of the reinforcing angle had occurred, as shown in Figure A13. Some localized pitting was evident at depth as well as an overall black discoloration of the steel as shown in Figure A14. In general, the grillage steel was in reasonably good condition.

At Tower 80, the E_{corr} reading on the northwest leg was -0.39 volts at a depth of 0.6 m. On the southwest leg, E_{corr} = -0.41 volts at a depth of 0.6 m. The most striking feature of this particular tower was that both the northwest and southwest footings did not have reinforcing angles placed at ground line as shown in Figure A15. In addition, the soil around these footings had been built-up around the much thinner lattice steel, as shown in Figure A16. Underground corrosion of this type of steel member could have severe consequences for the stability of the tower. Due to the absence of reinforcing angles on two of the four footings, no further excavating was conducted at this site. The presence of a reinforcing angle can be detected at ground line by observing the thickness of the outer most steel angle which should approach 0.5 inches (1.27 cm) (see Figure A17).

Corrosion potentials at Tower 142 changed from -0.69 volts at a depth of 0.45 m to -0.72 volts at 1.68 m. These potential values correspond to relatively newer steel which was confirmed by visual inspection. This tower had been elevated by 2.4 m on new steel and new reinforcing angles had been installed some time in the recent past. Although no visual evidence of corrosion could be found, the I_{corr} value of 1 mA associated with this tower indicates that some corrosion activity is taking place, at a relatively higher rate, on the newer steel. This tower is also located in a very low, wet area next to a river south of Kitchener.

In summary, based on occasional visual inspections and E_{corr}/I_{corr} measurements, the grillage footings from this 80-year-old transmission line are still in reasonable condition. However, care must be taken to ensure that reinforcing angles have been placed on all footings and that soil has not been piled up around the lattice steel of the towers. This must be achieved by close inspection of all tower sites along this transmission line.

3.0 Dundas TS to Brant TS (B12/B13)

Circuit B12/B13 is a 115-kV transmission line linking, in part, Dundas TS to Brant TS in Central Region. This line covers a distance of 36.45 kms and consists primarily of 248 steel tower structures. The in-service date for this line was November 1, 1910. A total of 99 towers were inspected along this line which represents a coverage of 20%, or 1 in 5. Results of the survey are tabulated in Table A3 and selected results are plotted in Figures A18 to A20.

The average of corrosion potentials, as plotted in Figure A18, is -0.57 volts. The values have a wide range, from approximately -0.5 to -0.65 volts, which may be indicative of the heterogeneity in the original galvanized steel quality or in the nature of the corrosion environments traversed by the tower line. Based on these E_{corr}-values, it appears that the grillage steel is generally in better condition than in the two previous lines investigated, even though the in-service dates are virtually the same.

Towers numbered between 120 and 170 have corrosion potentials which are anomalously low, ie -0.5 volts. This particular area is where the tower line crosses over the Niagara Escarpment where surface and groundwater is relatively faster. This would be a much higher oxygenated environment which would tend to promote corrosion activity and lower corrosion potential values. This area also happens to be where the Toronto, Hamilton and Buffalo railway line is in closest proximity to the tower line. If trains using this line were powered by electricity in the past, stray currents may have promoted even more corrosion activity.

Corrosion currents, as plotted in Figure A19, average 0.9 mA which is double the values measured on the two previous lines (B5G/B6G and D7G/D9G). The area of consistently low I_{corr}-values is between Towers 140 and 190. This tends to correlate reasonably well with the soil resistivities measured along the tower line and plotted in Figure A20. The soil resistivities, which fall into the moderately corrosive environment, are associated with shallow water, lacustrine, deltaic and outwash sands/15/. Soil resistivities classified as corrosive, ie <5,000 ohm-cms, are associated with Halton till in the eastern portion of the tower line and with lacustrine, varved clays and silts in the western portion.

Severe corrosion was found at Legs 1 and 2 of Tower 165, where 1/2 of the thickness of the lattice steel members had corroded away at ground line. The average corrosion potential of these two legs was -0.477 volts which is indicative of corroding steel but the corresponding average corrosion current was only 0.31 mA. In general, the condition of the ground line steel inspected along this transmission line was reasonably good, having suffered only moderate amounts of surface corrosion and pitting.

In summary, a contradiction has developed from the performance of this survey. Areas of low soil resistivity tend to correlate well with areas of higher corrosion currents; however, some areas correlate with more electronegative corrosion potentials which are indicative of less corroded steel.

4.0 Brant TS to Woodstock TS (B2W/B8W)

Circuit B2W/B8W extends between Brant TS and Woodstock TS in Western Region. This 115-kV transmission line, which covers a distance of 35.13 kms, consists mostly of 230 steel tower structures. The in-service date for this line was November 1, 1910. A total of 45 towers were surveyed, which represents 20% of the structures or 1 out of 5. The results are tabulated in Table A4 and selected values are plotted in Figures A21 to A23.

The corrosion potentials, plotted in Figure A21 average -0.57 volts. Between towers 15 to 40, the corrosion potentials are approximately -0.45 volts which indicates that the grillage steel has corroded to some degree. This was confirmed by the ground line visual inspections where the steel was found to be moderately corroded and pitted. The most severe corrosion was observed at Tower 15 where the thinner lattice steel was below ground level again. Approximately one-half of the tower sites inspected had E_{corr} values at or above -0.6, which indicates that some minor corrosion has taken place.

Once again, the areas where potentials are at or above -0.6 volts, ie less corroded steel, were areas where corrosion currents were also the highest (>1 mA in Figure A22a). These areas also tend to correlate with soil resistivities at or less than 4,000 ohm-cms (see Figure A23a). These areas of higher corrosion currents and lower resistivities did not reveal higher frequencies of visible corrosion upon inspection of the footings at ground line.

The difference in corrosion potentials between eastern and western portions of the circuit are significant (-0.45 to -0.65 volts). The proximity of the Grand River basin and two separate railway lines to Brant TS, may have contributed to higher corrosion activity in the past even though present day corrosion current values are low.

The relationship between E_{corr} and I_{corr}, which has developed through surveying of B12/B13 and B2W/B8W, is that corrosion activity will be relatively higher on newly corroding steel, but will eventually decrease when enough corrosion products have built-up.

5.0 Woodstock TS to Buchanan TS (W7W/W8W)

Circuit W7W/W8W extends from Woodstock TS westwards to Buchanan TS within the City of London. This 115-kV transmission line covers a total distance of 45.1 kms and was put into service on December 1, 1910. A total of 53 towers were surveyed representing approximately 20% of the structures along this transmission line. The results of the survey are tabulated in Table A5 and selected values are plotted in Figures A24 to A26.

The corrosion potentials plotted in Figure 24 average -0.56 volts and, in general, range from -0.5 to -0.6 volts. This indicates that the galvanizing layer on the original steel has corroded away and that moderate steel corrosion has taken place. The first 40 towers, near Woodstock TS, have the lowest potential readings (-0.47 volts). Once again, this may be due to their proximity to the Thames River, west of Woodstock.

The corrosion currents plotted in Figure A25 average 0.5 mA and are consistently between 0 and 1 mA. These lower I_{corr} values may be correlated to the fact that soil resistivities, measured along this tower line, were generally above 4,000 ohm-cms. The variability in soil resistivities plotted in Figure A26, are indicative of the wide variety of soil types transversed by the tower line east of London.

Based on visual inspections of the grillage steel just below ground line, no obvious patterns of corrosion activity were detected. In general, the ground line steel is in good condition, with the following exceptions: moderate to heavy corrosion was observed at Towers 4, 25, 30, 50, 130, 156, 175, 200, 235 and 275. This level of corrosion included severe pitting with some overall metal loss.

6.0 Leong Jct to St. Mary's TS (D8S/D10H)

This portion of circuit D8S/D10H extends between Leong Jct to St. Mary's TS in Central Region. This portion covers a total distance of 56.62 kms and consists, in part, of 260 steel tower structures. Stratford TS is located approximately in the middle of the section of line (Tower 240). The in-service date for this 115-kV transmission line was December 1, 1910. A total of 52 towers were surveyed, representing 20% of the structures along the tower line. The results of the survey are tabulated in Table A6 and selected results are plotted in Figures A27 to A29.

Based on the corrosion potentials plotted in Figure A27 the average potential is equal to -0.55 volts and the range of values is between -0.5 and -0.6 volts. There seems to be a higher frequency of electronegative potentials (<-0.5 volts) along the eastern portion of the tower line, between Leong Jct and Stratford TS. The overall corrosion potential values indicate that the galvanizing layer of the grillage steel has corroded away and that steel corrosion has occurred. The last tower surveyed, #379, exhibited an exceptionally high corrosion potential of -0.41 volts. This may be due to the proximity of St Mary's TS and its associated grounding grid.

The corrosion currents are plotted in Figure A28. These I_{corr} values average 0.85 mA which is similar to the I_{corr} average for B12/B13 and B2W/B8W discussed in previous sections. In general, the currents measured along D8S/D10H are less than 1.5 mA and there may be a slight tendency for I_{corr} values to increase west of Stratford TS (Tower 240). This correlates with decreased soil resistivities as plotted in Figure 32a.

The soil resistivities measured along the transmission line are generally below 4,000 ohm-cms which classifies the soils as corrosive. The pattern of decreasing soil resistivities for east to west correlates with the changes in physiography as described by Chapman and Putman/16/. The soil types near Leong Jct are associated with the Easthope Kame moraine and are therefore predominantly sands and silty sands. Further to the west (Tower # >200), the physiography changes to that of a till plain where the soils are predominantly clayey silts.

The result of the shallow visual inspections below ground line was that the grillage steel is generally in good condition and has suffered only slight corrosion at ground line. There is a tendency for the level of corrosion to increase on the portion of the line west of Stratford TS where there is a higher frequency of moderate corrosion and pitting of the ground line steel. Based on these results, it may be concluded that potential readings between -0.5 and -0.6 volts are indicative of minor corrosion on grillage members.

7.0 St Mary's TS to Devizes Jct (L7S)

This portion of circuit L7S extends west from St Mary's TS to Devizes Jct in Western Region. This portion covers a total distance of 14.92 kms and consists mostly of 100 steel tower structures. This portion of the line was put into service on December 1, 1910. A total of 20 towers were surveyed along this line, representing 20% of the structures present. The results of the survey are tabulated in Table A7 and selected results are plotted in Figures A30 to A32.

The average of the corrosion potentials plotted in Figure A30 is -0.55 volts which is identical to the average E_{corr} obtained from the survey of Leong Jct to St Mary's TS. The range of values is once again between -0.5 and -0.6 volts, but a few readings were less than -0.5 volts near St. Mary's TS. This may be indicative of the influence of the local grounding grid on the potential readings.

The average of the corrosion currents, plotted in Figure A31 is 0.85 mA which is identical to that obtained on the Leong Jct to St. Mary's TS line. The corrosion current values are greater than 1 mA between Towers 20 and 40 which correlates well with the area of lowest soil resistivity as plotted in Figure A32.

Based on soil resistivity measurements, the soils along the tower line may be classified as corrosive. However, based on the shallow visual inspections of the grillage footings, the ground line steel is still in good condition having suffered only minor surface corrosion and pitting.

8.0 Kent TS to Windsor Leong TS (K6Z)

Circuit K6Z extends between Kent TS westwards through Tilbury TS, Belle River Jct and Windsor Lauzon TS in Western Region. This line covers a total distance of 67.42 kms and consists mostly of 344 steel tower structures. The in-service date for this line was August 1, 1914. A total of 67 towers were surveyed representing approximately 20% of the structures present. Results of the survey are tabulated in Table A8 and selected values are plotted in Figures A33 to A35.

The average of the corrosion potentials plotted in Figure A33 is -0.65 volts and the values range from -0.6 to -0.7 volts. This should indicate that the galvanizing layer has corroded away, but that steel corrosion has not occurred to the same degree as on tower lines reviewed in previous sections. This could be due to the fact that K6Z was put into service 4 years after the other tower lines were. As noted in the previous sections, the corrosion potential values tend to decrease in the vicinity of transformer station grounding grids. This is shown by the plot on Figure A33a where potential lows occur at Kent, Tilbury, Belle River and Windsor Lauzon.

The average of the corrosion currents plotted in Figure A34 is equal to 2.14 mA which is more than double any previous I_{corr} values reported. From east to west, the corrosion current values rise to 3 mA and then range from 2 to 3.5 mA until Belle River Jct (Tower 255). West of Belle River Jct, I_{corr} values range from 1 to 2.5 mA until Lauzon TS. This decrease in corrosion currents cannot be explained by a change in soil type since it remains relatively constant as shown by the plot of soil resistivity in Figure A35a. These soil resistivities fluctuate between 2,000 and 5,000 ohm-cms along the entire transmission line, which classifies them as corrosive soils. These soils belong to the physiographic region known as the Essex Clay Plain/16/.

The high corrosion currents associated with the footings of K6Z do not correspond with the results of the shallow visual inspections of the steel below ground line. Only between Towers 4 and 25 was there a consistent level of moderate corrosion and pitting. The large majority of grillages inspected, showed very little evidence of corrosion below ground line with a few important exceptions. The ground line steel at Tower 335 (near Windsor Lauzon TS) showed signs of severe corrosion, pitting and flaking and the original stub angle was almost completely corroded away. Only the presence of a reinforcing angle has kept this tower from failing. Other such cases were found west of Belle River Jct and these will be discussed in a later section along with the results of a more detailed survey.

A Union Gas pipeline runs parallel to most of the transmission line surveyed. In fact, the pipeline happens to occupy the transmission line right-of-way west of Belle River Jct. This pipeline is cathodically protected using several rectifier/anode bed systems along its length. The objective of the more detailed survey was to determine if the presence of the pipeline had any influence on the E_{corr} and I_{corr} readings taken on the grillage footings. The preliminary results of this survey are be discussed in section 4.2.

9.0 Dundas TS to Glanford Jct (B3/B4)

This portion of circuit B3/B4 extends from Dundas TS to Horning Mountain Jct and then to Glanford Jct in Central Region. This portion covers a total distance of 13.21 kms and consists primarily of 73 steel tower structures. The in-service date of this line was February 1, 1915. A total of 13 towers were inspected during this survey, representing approximately 18% of the structures present. The results are tabulated in Table A9 and selected values are plotted in Figures A36 to A37.

The average of the corrosion potentials measured along this line is -0.64 volts, however, the range of values is quite large, from -0.5 to -0.84 volts. The higher potentials exhibited by Towers 82, 85 and 90 may be related to the fact that they are heavier anchor towers used for crossing the Niagara Escarpment south of Hamilton. The remaining potentials, between -0.5 and -0.65 volts, indicate that some minor to moderate corrosion has occurred to date.

The corrosion currents, plotted in Figure A37 average 0.96 mA, which is closer to average values obtained on previous surveys. The I_{corr} values peak at over 2 mA for Tower 82 and then exhibit a slow decrease as the tower line crosses the Escarpment and turns east.

The results of the shallow visual inspections indicate that the ground line grillage steel is still in good condition. The only exceptions are Towers 100 and 105 which showed evidence of slight to moderate corrosion and pitting, but no significant metal loss.

10.0 Allanburg W. Jct to St. Ann's Jct (Q2A/Q8TG, A11T/A8W)

The portion of the transmission line corridor studied extends from Allanburg Jct (south of Thorold) westward through Rosedene Jct and St. Ann's Jct in Western Region. This particular survey covered a total distance of 25.85 kms. Three transmission lines occupy this corridor as shown in Figure A38. The circuits surveyed were Q2A/Q8TG (on the right of Figure A38) and A11T/A8W (in the middle of Figure A38). Circuit Q2A/Q8TG consists mostly of 146 steel tower structures, however, the first 83 towers were put into service on October 1, 1910 and the remaining 63 towers were put into service on December 19, 1915. A total of 30 towers were inspected along this circuit which represents 20% of the structures present. The portion of circuit A11T/A8W surveyed consists of 89 towers that were in service on June 9, 1929. A total of 25 towers were actually inspected along this circuit, which represents 28% of the steel structures present.

The purpose of inspecting these two tower lines within the same corridor was to determine the effect of different in-service dates on the corrosion potentials and corrosion currents measured with the TLIM. The difference in in-service dates is between 14 and 19 years. There are also fewer towers along circuit A11T than along Q2A which implies that the tower spans are longer on the former than the latter. The longer tower span implies that the structures of A11T are larger and heavier and should consequently have larger grillages. This may also have influenced the corrosion measurements taken.

The results of these two surveys are provided in Tables A10 and A11 and selected values are plotted in Figures A39 to A41.

The average of the corrosion potentials for Q2A, plotted in Figure A39a is -0.64 volts. However, this value is somewhat misleading, since for the oldest part of the circuit, between Allanburg W. Jct and Rosedene Jct (in-service date = 10.10.01), the E_{corr} values tend to fluctuate between -0.5 and -0.6 volts. For the relatively newer part of the circuit, between Rosedene and St. Ann's Jcts (in-service date = 15.12.19), E_{corr} values tend to fluctuate between -0.6 and -0.7 volts. This difference in corrosion potential values may not be entirely due to the difference in ages. The eastern portion of the transmission line corridor passes through an extensive drainage basin associated with Twelve Mile Creek and the Niagara Escarpment (see Figure A42). The steeper topography in this area promotes quicker drainage of surface and subsurface waters. This creates a more oxygenated environment which tends to promote accelerated corrosion.

The plot of corrosion potentials versus tower numbers for circuit A11T (Figure A39a) shows a similar dip in values east of Rosedene Jct. The E_{corr} values in this area are below -0.7 volts, whereas the remaining values average -0.8 volts. The difference in magnitude of corrosion potentials between Q2A and A11T can be attributed to their age and structural differences.

The corrosion currents for both Q2A and A11T are plotted in Figure A40. The general trends in I_{corr} values tend to follow the trend of soil resistivities plotted in Figure A41. Soil resistivities of greater than 4,000 ohm-cms, between Towers 90 and 110, are associated with corrosion currents of less than 1 mA. The majority of soils along the transmission line corridor have soil resistivities between 2,000 and 3,000 ohm-cms. The associated corrosion currents, for both circuits, range from 1 to 4 mA which is similar to the range of values determined for circuit K6Z. The peak in corrosion currents between Towers 125 and 145 may be due to the proximity of Rosedene Jct and associated interferences. A pipeline crosses over exactly at this location and a tributary of Fifteen Mile Creek also crosses over in the same vicinity. This combination of circumstances may have conspired to produce the higher I_{corr} values, however, the corresponding potentials have not been affected similarly. The only significant difference in corrosion currents between the two circuits is that I_{corr} for Q2A tends to fluctuate more along the transmission corridor than A11T.

The results of the shallow visual inspections along Q2A indicate that the ground line steel on the grillages is still in reasonable condition, having suffered slight corrosion and pitting as shown in Figure A43. There were a few important exceptions. The original stub angles on Tower 91 of Q2A have suffered severe corrosion and metal loss at ground line, as shown in Figure A44. Below ground level, the stub angles show evidence of moderate corrosion, pitting and flaking as shown in Figure A45. This level of corrosion activity is associated with silty sand. At Tower 100, on circuit Q2A, the tower steel is below ground line. This situation has been observed along other tower lines and in almost all cases the thinner tower steel has deteriorated significantly due to corrosion (see Figure A46).

From visual inspections along circuit A11T, it can be concluded that these 60-year-old grillage footings are still in very good condition, as shown in Figure A47.

The results of inspections on both Q2A and A11T are better represented by the corrosion potentials than by corrosion currents.

11.0 Trafalgar Jct to Nelson Jct (K7B/K8B)

This portion of circuit K7B/K8B extends from Trafalgar Jct through Palermo Jct to Nelson Jct in Central Region. The total distance covered by this portion of the line is 22.91 kms and the in-service date was July 1, 1922. A total of 25 towers were surveyed representing 20% of the 125 towers present. The results of the survey are provided in Table A12 and selected values are plotted in Figures A48 to A50.

The average corrosion potential is -0.69 volts and the values range from -0.6 to -0.75 volts. These values indicate that the galvanizing layer has corroded away on most of the footings, most notably near Towers 145 and 170, but the steel should still be in good condition. The corrosion potential lows (-0.6 to -0.65 volts) are associated with towers crossing Sixteen Mile Creek and Bronte Creek, east and west respectively, of Palermo Jct. A potential survey was completed in June, 1970 along the same right-of-way and the average potential value was approximately -0.9 volts. This value appears rather high, especially for a tower line that had been in-service for 48 years with no direct form of cathodic protection. An oil pipeline buried along the same right-of-way may have had some influence on the earlier readings, however, it is also possible that the use of a different instrument for acquiring the potentials has caused the discrepancy in values.

The average of corrosion currents plotted in Figures A49 is 0.99 mA, which is in line with much of the I_{corr} readings obtained from other tower line surveys. This average is also similar to the one obtained during a survey of another Oakville line which parallels K7B/K8B in the same right-of-way (I_{corr} = 0.9 mA), but was put into service in 1911. There is no apparent correlation between I_{corr} and soil resistivities which, for the most part, equal 3,000 ohm-cms in the reddish-brown, sandy silt.

The results of the shallow visual inspections is that the grillage steel at ground line is still in good condition. An example of the slight corrosion observed during the survey is shown in Figure A51, which is a picture of Leg #3 at Tower 200.

12.0 Ottawa Hawthorne TS to Merivale TS (M31A)

This 230-kV transmission line extended from Ottawa-Hawthorne TS through Ottawa (Albion) TS to Merivale TS in Eastern Region. The total distance covered by this line was 12.02 kms and it consisted of 36 steel tower structures. The in-service date for this circuit was October 20, 1932 which makes it the youngest tower line surveyed in 1989. A total of 34 towers were surveyed, representing 94% of the steel structures present. The results of the survey are provided in Table A13 and in Figures A52 to A54.

The average of the corrosion potentials is -0.74 volts, which indicates that the grillage steel should still be in good condition. The potential values, plotted in Figure A52, were very consistent from Hawthorne TS to Ottawa (Albion) TS (Towers 323 to 334). West of Tower 334, the potentials tend to fluctuate significantly between towers. Coincidentally, before the survey was conducted, the towers and conductors west of Tower 334 had already been removed. It is unclear at this time, if the isolation of individual footings had an effect on the corrosion potential values.

The average corrosion current of M31A was 0.55 mA which indicates a very low level of corrosion activity. Corrosion currents above 1 mA were measured east of Ottawa (Albion) TS. This tends to correlate with soil resistivities less than or equal to 4,000 ohm-cms as plotted in Figure A54.

The result of the shallow visual inspections was that the grillage steel at ground line was still in excellent condition as no evidence of steel corrosion was found. Since the towers of M31A were removed because of construction of a new transmission line in the same corridor, the opportunity to completely remove certain grillage footings presented itself. Based mainly on differences in corrosion current levels, one grillage from Towers 330, 331, 335 and 337 were completely removed for closer inspection. The results of this examination are discussed in Section 4.1.

TABLE A1

Circuit: B5G/B6G
Section: Harper's Jct x Guelph Cedar TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
48	0.658	0.144	8500	15.7	7.3	
50	0.524	0.841	2100	23.6	7.2	x
52	0.619	0.441		17.6	7.4	x
54	0.56	0.187	4100	16.6	7.1	
56	0.586	0.223			7.6	x
60	0.57	0.21	8200	19.9	6.6	
65	0.576	0.24	17200	5.2	7.6	x
75	0.55	0.18	6900	11.3	7	x
90	0.532	0.21	6800	12.2	6.4	
92	0.568	0.28				
97	0.612	1.2				
98	0.635	1.28				
99	0.581	0.33				
104	0.456	0.256	6800		6.9	
105	0.474	0.108	4900	28.1	6.6	
116	0.489	0.144	8200	13.2	7.1	x
118	0.516	0.173				
120	0.515	0.333	4100	27	7.1	x
126	0.402	0.155				
127	0.416	0.25				
128	0.495	0.55				
129	0.42	0.16				
130	0.377	0.18				
135	0.391	0.28				
136	0.369	0.18				
137	0.397	0.3				
138	0.391	0.182				
139	0.38	0.234	10900	12.2	6.5	x
140	0.398	0.2				
141	0.402	0.286				
145	0.397	0.108	8400	13.6	6.8	
150	0.399	0.366	5100	17.4	7.5	x
155	0.396	0.106	7700	14.1	6.4	x
160	0.455	0.124	7500	13.1	7	x
165	0.475	0.29	7400	15.3	6	
170	0.48	0.34	11100	20.2	6.6	x
175	0.554	0.52	2500	14	7.3	x
181	0.464	0.09	6000	26	6	x
185	0.493	0.099	8600	17.1	7	x

TABLE A1

Circuit: B5G/B6G
Section: Harper's Jct x Guelph Cedar TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
190	0.465	0.2	10400	17.4	6.6	
195	0.482	0.13	5000	14.2	6.9	x
200	0.457	0.3	6600	20.9		
205	0.476	0.28	6900	19.8	6.2	x
210	0.538	0.59	4100	26.5	6.7	x
215	0.502	0.27	7500	20.4	7.4	
219	0.426	0.33	12000	19.1	5.8	x
225	0.522	0.46		18.4	6.7	x
228	0.464	0.299	7800	19.9	6.2	x
232	0.41	0.045	15500	5.3	6.8	x

TABLE A2

Circuit: D7G/D9G
Section: Guelph Cedar TS x Freeport Jct

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
3	0.56	0.144	6000	19.2	6.2	x
10	0.579	0.315	2150	30	7.3	x
20	0.556	0.35	5150	22.1	6.2	x
25	0.594	1.37	4050	22	6.8	x
30	0.567	0.72	8400	15.6	7.3	x
35	0.475	0.17	8100	15.2	6.8	
40	0.484	0.236	4800	21.1	6.3	
45	0.488	0.27	9100	15	7	
50	0.482	0.249	5800	25.8	6.1	
56	0.503	0.77	7600	22.9	6.3	
60	0.497	0.26	7000	16.6	6.7	
66	0.534	0.18	4900	16.7	6.7	
70	0.53	0.099	6600	10.9	6.9	
75	0.448	0.37	12500	13.7	6.1	
80	0.394	0.18	9000	15.9	5.8	
84	0.48	0.2	5500	16.5	7	x
90	0.539	0.6	4000	49.8	6.1	
111	0.553	0.63	2450	113.7	6.2	x
119	0.618	0.58	5950	15.1	7.1	x
132	0.527	0.135	7750	9.3	6.8	
138	0.601	0.702	3800	21	6	
144	0.63	0.978	1700	44.5	7.1	
149	0.569	0.255	4300	15.5	6.5	x
154	0.541	0.198	8050	18.2	6.6	

TABLE A3

Circuit: B12/B13
Section: Dundas TS x Brant TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
90	0.5	0.29	8600	18.1	5.6	
95	0.61	0.655	3600	18.3	7.7	x
100	0.5	0.369	2100	16.1	7.9	x
105	0.589	1.463	2800	30.4	8.5	
111	0.589	1.112	3600	19.2	7.2	x
115	0.565	0.713	2500	19.8	8.4	x
120	0.595	2.511	2900	29.7	7.7	
125	0.544	0.268	5400	13.1	7.5	x
130	0.508	1.032	2950	22.7	7.6	
137	0.54	0.632	9000	26.4	5.8	
141	0.528	0.891	2750	24.1	7.8	x
145	0.497	0.344	2700	21.9	8.1	
150	0.532	0.436	6150	23.3	6.9	
155	0.516	0.54	8400	24.3	4.4	
160	0.488	0.25	11000	23.9	6.2	
165	0.487	0.272	5000	20.6	6.9	
169	0.46	0.27	7750	24.3	6.4	
175	0.514	0.324	8900	18.6	5.3	
181	0.582	0.459	8000	28	6.2	
185	0.557	0.317	4950	28.1	5.6	
190	0.567	0.83	6800	37.5	5.5	
195	0.578	1.384	7000	29.8	6.9	
200	0.637	1.539	4650	29.5	7.6	x
205	0.618	0.472				
210	0.625	0.45	6700	22.4	6.9	
215	0.616	0.657	5650	25.7	6.4	
220	0.634	1.361	10150	24.7	6.9	
225	0.554	0.49	15500	20.3	6.5	
230	0.564	0.884	2700	27.3	8.2	x
235	0.579	0.236	8150	15.2	7.2	x
240	0.592	0.882	3500	24.1	7.9	x
245	0.597	1.13	2800	24.9	7.9	x
250	0.575	0.731	2700	27.7	7.5	x
255	0.622	1.231	3750	23.1	7.6	x
260	0.629	1.476	4100	30.4	6.8	
265	0.608	0.814	6850	22.4	6.9	
270	0.616	1.194	2800	21.9		x
275	0.626	1.292	3350	27		x
280	0.678	1.395	3450	27.3		x
285	0.651	0.612	5200	32.5	7.4	
290	0.609	1.595	3400	24.4	7.8	x

TABLE A3

Circuit: B12/B13
Section: Dundas TS x Brant TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
295	0.576	1.444	3150	29.8	7.7	
300	0.617	1.404	6700	26.7	6.5	x
305	0.615	2.455	1200	25.2	8.7	x
310	0.518	1.05	6400	28.8	5.4	
315	0.54	1.195	5000	33	7	x
320	0.531	0.789	7500	33.4	6	
325	0.534	0.292	5200	28.1	6.7	x
330	0.489	0.387	5600	33.6	6.5	

TABLE A4

Circuit: B2W/B8W
Section: Brant TS x Woodstock TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
5	0.525	0.358				
10	0.556	0.252				
15	0.457	0.313	5000	22.2	6.5	x
20	0.424	0.394	6300	19.9	7.4	x
24	0.454	0.358	6600	22.9	6.4	
30	0.442	0.256	6200	22.1	6.9	
35	0.463	0.399	5950	26.2	5.8	
40	0.457	0.252	5650	11.4	7.5	x
45	0.497	0.567	5300	22.7	6.8	x
50	0.566	0.4	8100	17	7.2	x
55	0.511	0.191	7200	22.6	6.8	
60	0.509	0.145	5800	23.6	6.8	
65	0.563	0.891	4100	13.7	6.9	x
70	0.523	0.349	6100	22.4	7.5	x
75	0.653	0.174	8200	10.5	7.3	x
80	0.516	1.343	3300	35.8	7.4	x
85	0.651	1.881	3000	22.6	8.1	x
90	0.679	1.97	2900	23.5	7.8	x
95	0.586	0.819	4750	18.5	8.1	x
100	0.535	0.189	7900	14.7	7.1	x
105	0.453	0.462	6800	16	7.6	
110	0.529	0.623	7300	17.3	7.5	
115	0.522	0.137	13500	13.6	6.2	x
120	0.584	0.551	6400	19.3	7.4	
125	0.6	0.864	5650	20.9	7.8	x
130	0.611	0.997	4600	24.4	8	x
135	0.648	1.26	3400	19.5	8.2	x
140	0.618	1.719	5000	23.3	7.4	x
145	0.635	1.617	3300	38	7.2	
150	0.576	0.914	4700	18.2	7.4	x
155	0.579	1.775	3200		7.5	x
160	0.585	1.022	5850	16.1	8.5	x
165	0.61	1.71	3500	19.6	8	x
170	0.661	1.197	4000	21.7	7.7	x
175	0.611	0.817	4800	22.5	7.2	
181	0.649	1.15	4750	18.5	7.4	x
185	0.635	1.171	3150	36.3	7.6	
190	0.675	2.212	1550	31.8	7.4	x
195	0.682	1.629	3400	29.8	7.9	x

TABLE A4

Circuit: B2W/B8W
Section: Brant TS x Woodstock TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
200	0.675	1.984	2100	27.5	7.5	
205	0.642	0.936	3150	25.3	7.7	
210	0.617	0.817	4000	26	7.3	
215	0.572	0.502	4900	23.4	7	x
220	0.576	0.808	7000	15.8	7.3	x
227	0.568	1.276	4850	23.7	8.1	x

TABLE A5

Circuit: W7W/W12W
Section: Woodstock TS x Buchanan TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
2	0.484	0.089	6300	18.8	7.8	x
4	0.523	0.42	8150	18.4	7.5	
20	0.468	0.308	4850	22.1	7.6	
25	0.52	0.446	7250	24.2	6.9	x
30	0.427	0.338	6200	30.2	6.8	
35	0.531	0.475	5700	28	6.8	
40	0.588	0.857	4700	32.5	7	x
45	0.59	0.855	3700	15.3	7.6	x
50	0.525	0.342	5700	23.5	6.2	
56	0.589	0.346	3400	29.5	7.5	
61	0.592	0.648	4300	20.3	7.8	x
65	0.557	0.554	4050	32.1	6.9	x
70	0.537	0.423	5800	17.4	7.6	x
75	0.533	0.159	7250	10.8	7.5	x
85	0.554	0.614	5500	22.5	6.9	
90	0.59	0.81	5250	18.2	7.7	x
95	0.588	0.621	4150	21.1	7	x
100	0.586	0.412	4700	23.2	9.6	x
105	0.571	1.125	3000	24.4	7.6	x
110	0.576	0.695	4650	22.6	7.1	x
115	0.585	0.61	3600	16.9	7.3	x
120	0.596	0.274	4050	18.6	8	x
125	0.58	0.267	4400	29.2	7.2	x
130	0.59	0.76	3300	25	8	x
135	0.559	0.533	5300	23.7	7.8	x
140	0.573	0.718	5400	21.4	8.1	x
145	0.566	0.459	4900	25.4	7.5	x
150	0.577	0.328	4700	20.3	8.1	x
156	0.54	0.612	5300	16.3	7.9	x
160	0.598	0.191	5500	15.9	8.1	x
165	0.525	0.364	5400	17.2	7.9	x
170	0.53	0.857	7450	14.5	7.8	x
175	0.496	0.628	3200		8.1	x
180	0.522	0.151	6600	12.2	7.8	x
185	0.579	0.765	7050	29.3	7.8	x
190	0.526	0.392	4320	18.6	8.1	x
195	0.5	0.621	4450	16.3	8.1	x
200	0.548	0.446	4300	20.8	7.9	x
205	0.579	0.166	8000	13.8	7.6	x

TABLE A5

Circuit: W7W/W12W
Section: Woodstock TS x Buchanan TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
210	0.599	0.093	8800	16.9	7.3	
215	0.627	0.93	4500	27.5	7.2	x
220	0.6	0.626	4900	19	7.9	x
225	0.616	1.098	4400	26.6	7.6	x
230	0.606	0.641	4700	16.6	8.1	x
235	0.581	0.417	5000	22.7	7.7	x
240	0.545	0.565	5575	17.1	7.5	
245	0.517	0.259	8130	11	6.7	x
250	0.56	0.511	6200	14.1	7.3	x
255	0.597	0.482				
260	0.601	0.902	4590	20.9	7.5	
265	0.562	0.49	10800	7	8.7	x
270	0.567	0.148	9400	10	7.8	x
275	0.505	0.364	6675	17.5	7.7	x

TABLE A6

Circuit: D8S/D10H
Section: Leong Jct x St. Mary's TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
115	0.578	0.821				
120	0.607	1.516				
125	0.627	1.056	3600	17.1	8.1	x
130	0.563	1.73				
135	0.554	0.956	4100	13.7	7.1	x
140	0.537	0.302				
145	0.562	0.459	4700	17.8	7.2	
150	0.554	0.774				
155	0.567	0.864	3700	12.5	6.8	
160	0.535	0.342				
165	0.494	0.106	5500	9.7	6.8	
170	0.47	0.648				
175	0.538	0.844	2475	23.9	7.8	x
180	0.528	0.77	3075	25.5	7.8	x
185	0.532	0.765				
190	0.5	0.439	4000	12.7	7.2	
195	0.563	0.92				
200	0.505	1.386	3700	23.8	6.4	
205	0.47	0.357				
210	0.58	1.098	2800	29.7	6.4	
215	0.564	0.554				
220	0.569	0.594	3050	23.1	6.4	
225	0.547	0.576				
229	0.49	1.071	3300	17.3	7.3	
239	0.503	0.39				
245	0.545	0.725	3100	24.9	6.5	
250	0.548	0.556				
255	0.569	0.904	2600	11.6	8.2	x
260	0.538	1.174				
265	0.547	1.071	3200	15.6	7.3	x
270	0.566	2.37				
275	0.711	0.706	3800	21.6	6.8	
280	0.515	0.961				
283	0.563	0.936	2150	23.8	7.6	x
290	0.537	0.9				
295	0.575	1.546	2100	27	6.5	x
299	0.565	0.785				
305	0.53	0.538	3300	15.5	7	x
310	0.514	0.616				

TABLE A6

Circuit: D8S/D10H
Section: Leong Jct x St. Mary's TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
315	0.54	0.621	3400	15.2	6.8	
320	0.542	1.084				
325	0.574	0.828	1500	27.1	6.7	
330	0.586	0.477				
335	0.545	0.808	2550	26.9	7.5	
340	0.567	0.781				
345	0.582	0.817	2400	22.8	7.8	x
350	0.6	1.231	2400	15.6	7.7	x
355	0.561	0.814	4000	15.2	7.2	
360	0.582	0.907				
365	0.58	0.904	2200	25.7	8	x
370	0.57	1.37				
379	0.41	0.346				

TABLE A7

Circuit: L7S
Section: St. Mary's TS x Devizes Jct

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
5	0.448	0.214				
10	0.474	0.13	4400	9.6	6.8	x
15	0.573	0.83				
20	0.579	1.102	2650	15.5	7.7	x
25	0.517	1.044				
30	0.556	1.514	2800	23.2	8	x
35	0.568	1.953				
40	0.579	0.945	2850	19.6	6.8	x
45	0.555	0.362				
50	0.495	0.889	2800	21.1	6.6	x
55	0.622	1.28				
60	0.539	0.846	3800	18.1	7.8	x
65	0.569	0.659				
70	0.57	0.254	3200	19	7.6	x
75	0.562	0.691				
80	0.549	0.508	6000	12.9	6.8	x
85	0.54	0.576				
90	0.561	0.922	3350	20.7	6.6	x
95	0.593	1.156				
99	0.525	1.08				

TABLE A8

Circuit: K6Z
Section: Kent TS x Windsor Lauzon TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
4	0.554	0.316				
9	0.578	1.03	3250	24.3	6.8	x
15	0.573	1.14				
20	0.61	1.58	5300	26.6	6.5	x
25	0.599	0.65				
30	0.625	1.1	4200	26.1	7.4	x
35	0.625	1.48				
40	0.619	1.92	3000	34.3	6.6	
45	0.623	1.34				
50	0.646	2.36				
55	0.636	3.16	2700	36.6	6.6	
60	0.645	2.87				
65	0.646	2.77	3100	36	6.8	x
69	0.654	2.62				
75	0.691	2.38	2500	31.5	6.7	x
80	0.707	2.6				
85	0.705	3.21				
90	0.701	1.67	5200		8.2	x
95	0.678	2.92				
100	0.672	2.28	2100		6.4	
105	0.667	3.44				
110	0.677	2.45	2900		5.9	
115	0.695	2.84				
120	0.694	2.54	2850	30.4	6.6	
125	0.666	2.39				
130	0.64	2.65	3200	27.8	6.4	
135	0.623	1.1				
139	0.662	2.32	3000	34.3	6.6	
144	0.661	1.79				
150	0.706	3.36	3875	36.8	6.5	
155	0.705	1.93	3100	12.8	5.5	
160	0.714	3.34				
165	0.704	2.5	3000	15.9	6.7	
170	0.684	2.94				
175	0.685	2.64	3300	11.9	6.1	
180	0.69	2.53				
185	0.683	2.82	3100	12.4	6.8	
190	0.67	2.49				
195	0.679	3.21	2950	14.8	6.4	

TABLE A8

Circuit: K6Z
Section: Kent TS x Windsor Lauzon TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
200	0.663	1.86				
205	0.66	3.14	2350	15.4	7.3	
210	0.683	2.8				
215	0.657	2.64				
220	0.667	1.82	2950	14.7	7.1	x
225	0.665	2.87				
230	0.658	1.62	4000	15.4	6.5	
235	0.667	2.47	3500	18.9	6.6	
240	0.659	2.15	3800	17.4	4.7	
245	0.602	3.64	4000	23.9	5.2	
250	0.646	1.37	4200	17.7	5.9	
255	0.619	1.11	3500	16	6.7	
259	0.625	2.26	3400	12.8	7	
265	0.659	1.61	4000	16.8	6	
275	0.658	1.85	3200	14.5	6.3	
280	0.668	2.76	1800	17.7	6.6	
285	0.656	2.14	2200	18.9	7.1	x
289	0.664	1.52	2500	14.8	6.7	
295	0.653	2.1	3250	14.7	6.5	x
300	0.665	2.28	3650	20.6	6.7	
305	0.774	1.13	4000	13.5	6	
310	0.6	0.121	3000	15.9	6.5	
315	0.642	1.4	3000	15.9	7.6	x
320	0.644	1.97	3650	16.6	6.8	
325	0.599	2.26	3400	20.7	6.9	
330	0.638	0.86	2850	14.3	7.3	
335	0.58	1.06	3100	13.9	7.3	
343	0.595	2.19	3350	15.1	7.6	

TABLE A9

Circuit: B3/B4
Section: Dundas TS x Glanford Jct

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
77	0.583	0.279				
82	0.729	2.162	2950	22.1	6.1	
85	0.839	1.676				
90	0.763	1.024	4350	20.7	5.9	
95	0.648	1.494				
100	0.584	0.3	7900	32.3	4.2	
105	0.5	0.612				
111	0.664	1.199	3050	33.2	6.9	x
115	0.634	0.9				
120	0.624	0.951	3350	24.5	7.1	x
125	0.552	0.66				
130	0.603	0.783	7200	26	4.6	x
136	0.592	0.49				

TABLE A10

Circuit: Q2A
Section: Allanburg W. Jct x St. Ann's Jct

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
61	0.65	1.267				
65	0.628	1.6	2700	33.7	7.5	x
70	0.779	1.658				
76	0.699	1.035	2800	22.2	7	x
80	0.61	1.058				
85	0.577	1.224	3100	20.6	7	
91	0.559	0.708				
95	0.572	0.558	5400	22.7	6	
100	0.494	0.561	4200	16.5	7.1	
105	0.515	0.313	8800	18	4.9	
110	0.577	2.338				
115	0.488	1.033				
120	0.622	2.475	2800	20.5	7.5	x
125	0.472	0.884	3100	21.3	5.9	
130	0.605	3.976				
135	0.697	3.332	2700	20.1	7.6	x
140	0.71	3.978				
145	0.728	4.138	2250	33.2	7.5	
150	0.653	1.236				
155	0.635	2.599	2400	26.9	7.7	x
160	0.623	2.311				
165	0.688	2.954	2400	26.4	8	x
170	0.707	1.971				
175	0.693	2.734	2400	21.4	7.6	x
180	0.664	2.18				
184	0.655	1.107	2700	20.9	7.4	x
190	0.656	1.802				
195	0.714	2.628	2000	30.3	7.4	x
200	0.697	1.875				
205	0.722	2.56	2400	17.5	8.3	x

TABLE A11

Circuit: A11T/A8W
Section: Allanburg W. Jct x St. Ann's Jct

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
67	0.783	2.297	3000	22.5	7.9	x
70	0.774	2.747				
74	0.785	1.204				
78	0.735	1.949				
80	0.652	1.35				
83	0.586	1.047	4300	21	6.9	x
92	0.674	0.867				
95	0.757	2.061	5500	19.8	6.5	x
100	0.821	1.042	3200	23.6	6.9	
103	0.806	2.201	1800	26.8	7.2	
107	0.75	1.465				
111	0.825	3.011				
112	0.644	4.165				
117	0.776	1.496	2900	33.4	7.4	x
119	0.833	1.575				
122	0.828	1.472	2600	25.3	7.8	x
124	0.79	2.02				
127	0.839	1.933	2000	30.8	7.1	x
130	0.794	1.231				
133	0.798	1.372	2250	26.1	7.3	x
136	0.754	1.544				
138	0.814	1.753	2700	29.1	6.7	
141	0.797	4.432				
144	0.823	1.455				
147	0.792	1.82				
149	0.77	1.125	2500	28.3	6.9	

TABLE A12

Circuit: K7B/K8B
Section: Trafalgar Jct x Nelson Jct

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
105	0.729	0.646				
110	0.7	1.098	3650	21	6.8	x
115	0.712	1.464				
120	0.728	1.184	2650	19.4	7.4	x
125	0.685	1.123				
131	0.682	1.022	3400	18.4	6.8	x
135	0.715	1.337				
140	0.624	0.297	5700	16.7	6.5	x
145	0.622	0.866				
150	0.662	0.956	4500	23	6.9	x
156	0.688	0.878				
160	0.661	1.134	2800	19.6	6.4	
165	0.686	1.078				
170	0.612	0.783				
176	0.622	0.988	2950	16.8	7.2	x
180	0.681	1.082				
185	0.671	0.502	3000	13.7	6.7	x
192	0.727	0.873				
195	0.741	0.999	2800	20.4	7.3	x
200	0.717	0.675				
205	0.72	0.641	3300	10.7	7.9	x
211	0.714	1.631				
215	0.702	0.958	3150	13.9	7.2	x
220	0.751	1.094				
225	0.754	2.039	2600	19.6	8	x

TABLE A13

Circuit: M31A
Section: Ottawa Hawthorne TS x Merivale TS

TOWER #	Ecorr (-V)	Icorr (mA)	Resistivity (ohm-cms)	M/C (%)	pH	Sulfide
323	0.767	0.28				
324	0.764	0.83	3750	35.4	6.2	x
325	0.734	1.25	3200	32.9	6.3	
326	0.779	1.31	3775	24	6.3	x
327	0.762	1.06	7000	28.5	6.7	x
329	0.767	0.5	5100	37.2	6.1	
330	0.765	1.24	4350	30.2	6	
331	0.758	1.43	5475	29.6	6.2	
332	0.75	0.936	7400	25.3	6.1	
333	0.775	0.63	5900	29.6	6.5	
335	0.764	0.29	13000	19.5	6.9	x
336	0.771	0.28	7300	24.4	7.5	
337	0.665	0.31	7400	8.7	8.4	x
338	0.677	0.445	4600	22	7.2	
339	0.773	0.49	3800	28.5	7.5	
340	0.795	0.23	21500	30.3	6.2	
341	0.82	0.25	8000	31.7	6.8	
342	0.705	0.157	8600	26.9	7.7	
343	0.792	0.47				
344	0.762	0.31	11000	16.5	7.4	x
345	0.735	0.61	12000	20.8	6.5	
346	0.864	0.68				
347	0.784	0.55	3200	23.4	7.4	x
348	0.865	0.075	8800	17.6	7.3	x
349	0.703	0.38	4700	36	6.6	
350	0.689	0.34	8250	25.2	6.5	
351	0.75	0.5	3900	42.4	6.3	
352	0.74	0.65	5500	25.3	6.2	
353	0.741	0.65	3500	28	7.4	
354	0.732	0.55	6300	27.1	7.2	
355	0.699	0.36	13000	27.4	6.2	
356	0.719	0.21	7000	7.5	8.4	
357	0.729	0.162	7700	35.5	7	x
358	0.435	0.36				

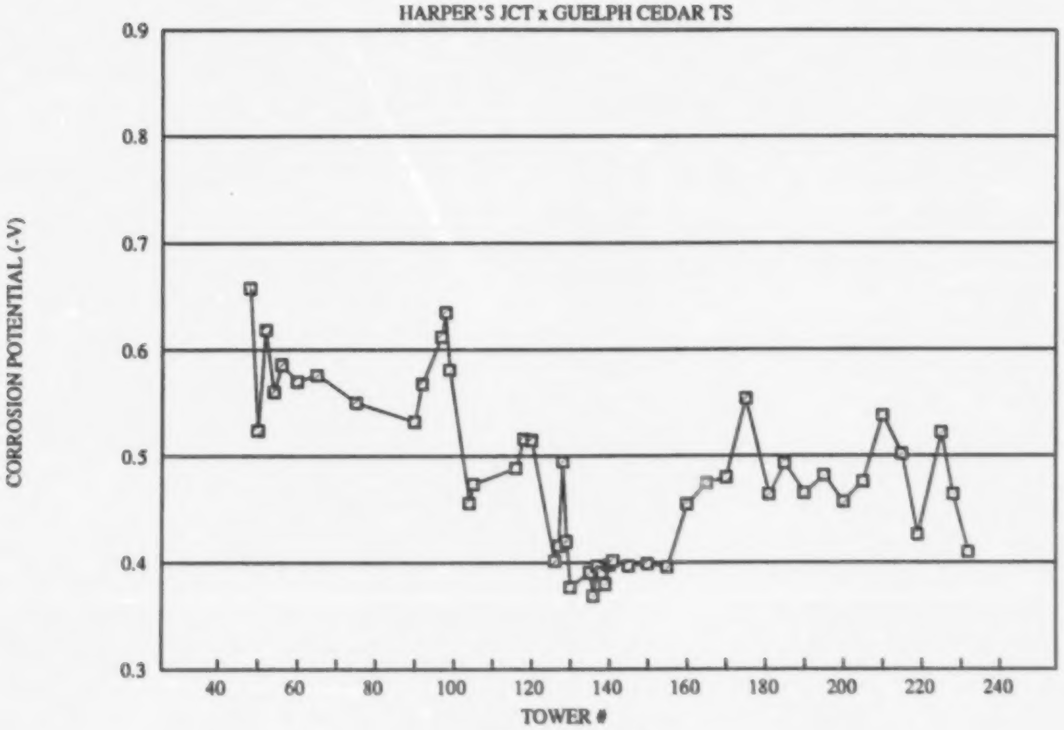


FIGURE A1a

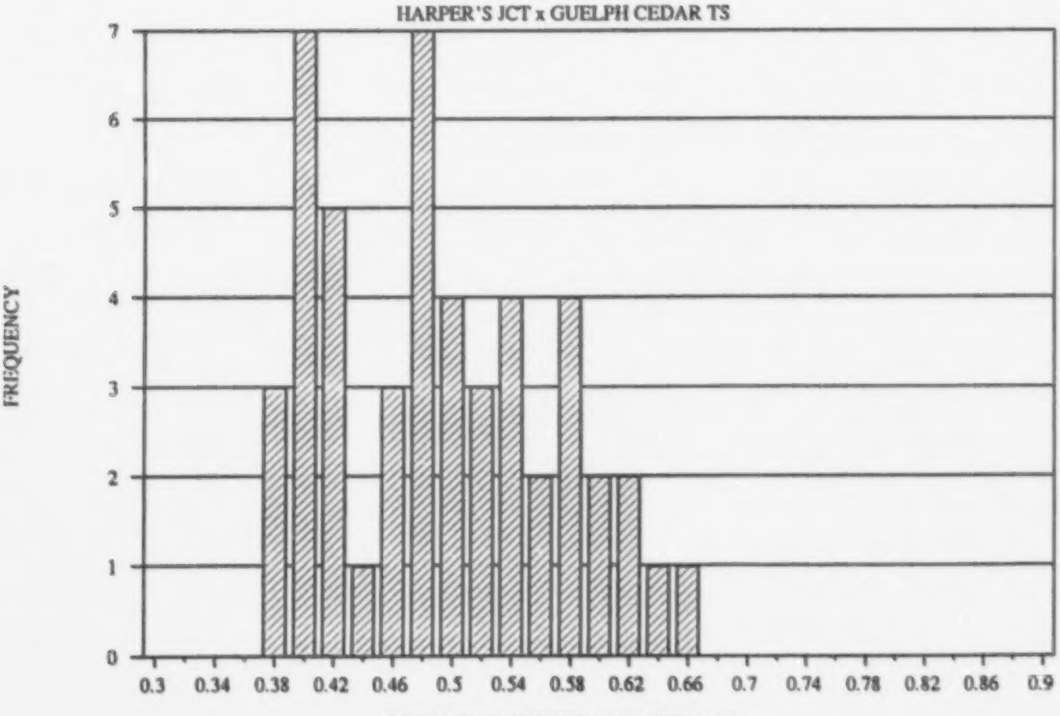


FIGURE A1b

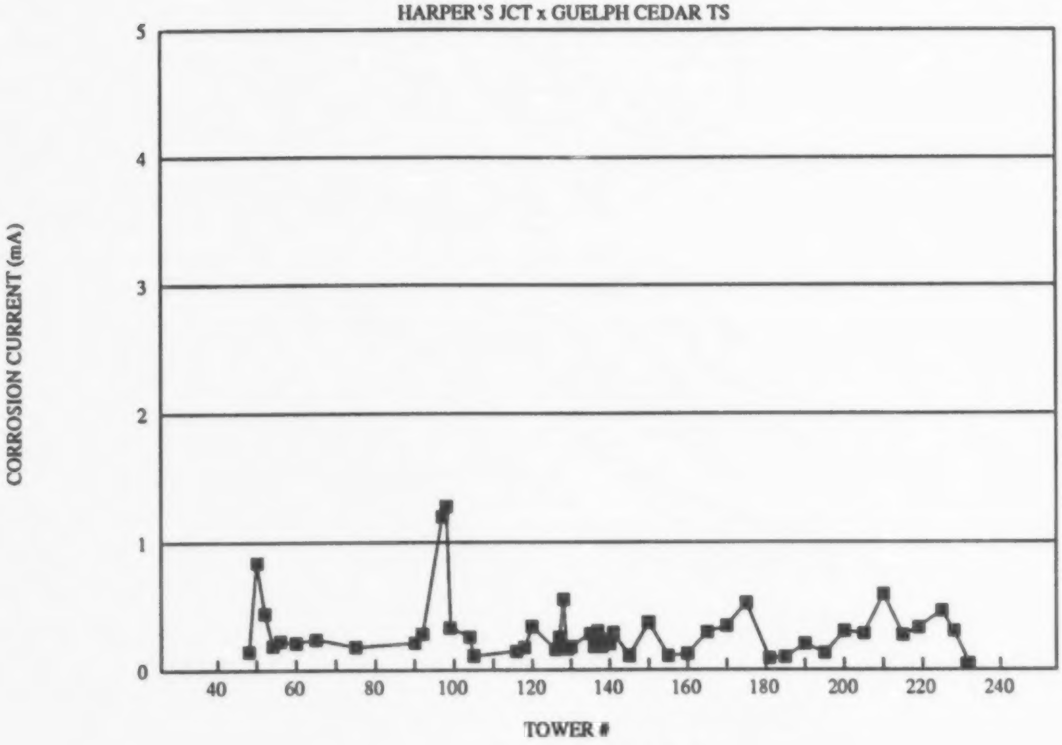


FIGURE A2a

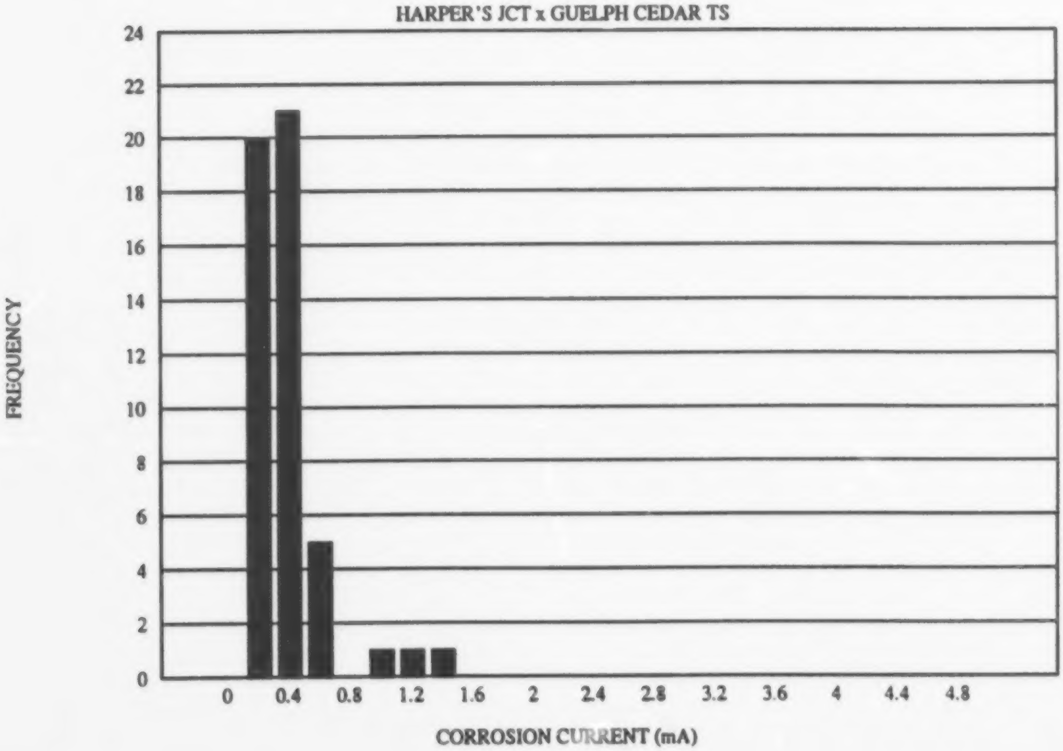


FIGURE A2b

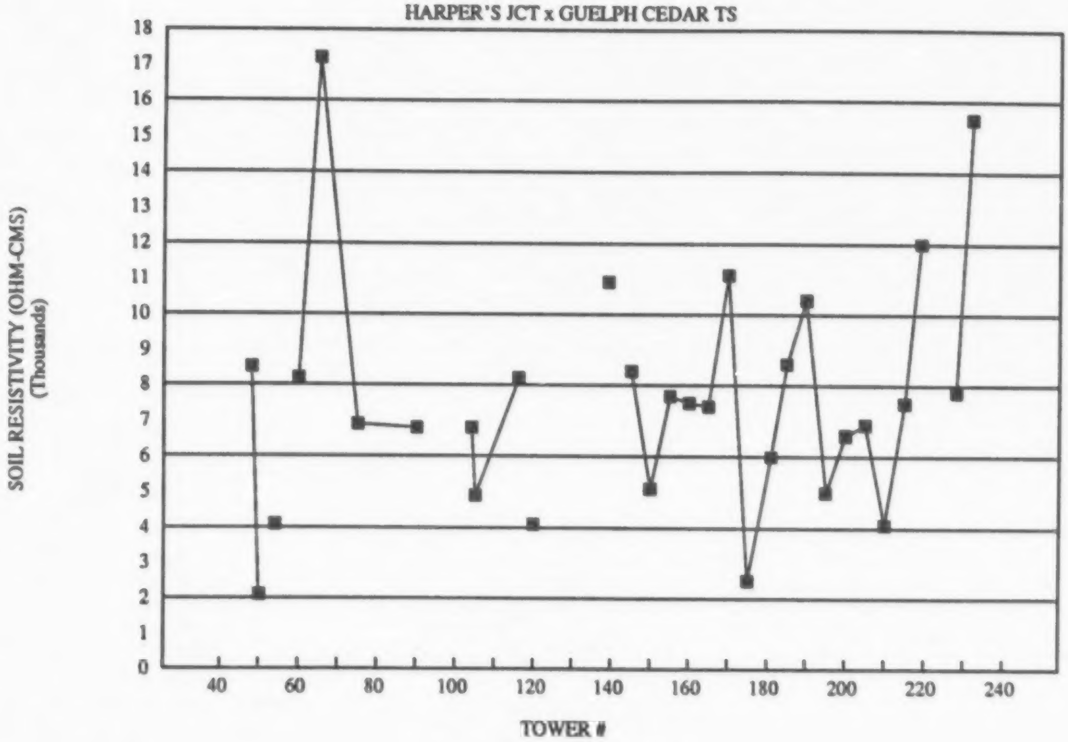


FIGURE A3a

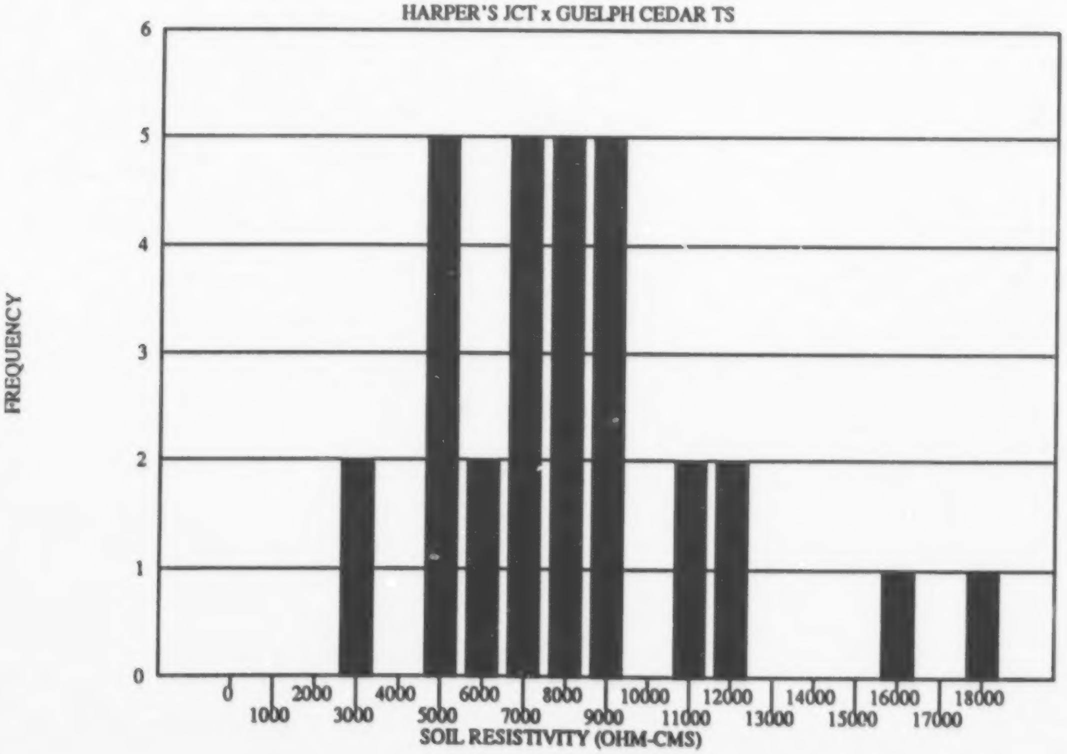


FIGURE A3b

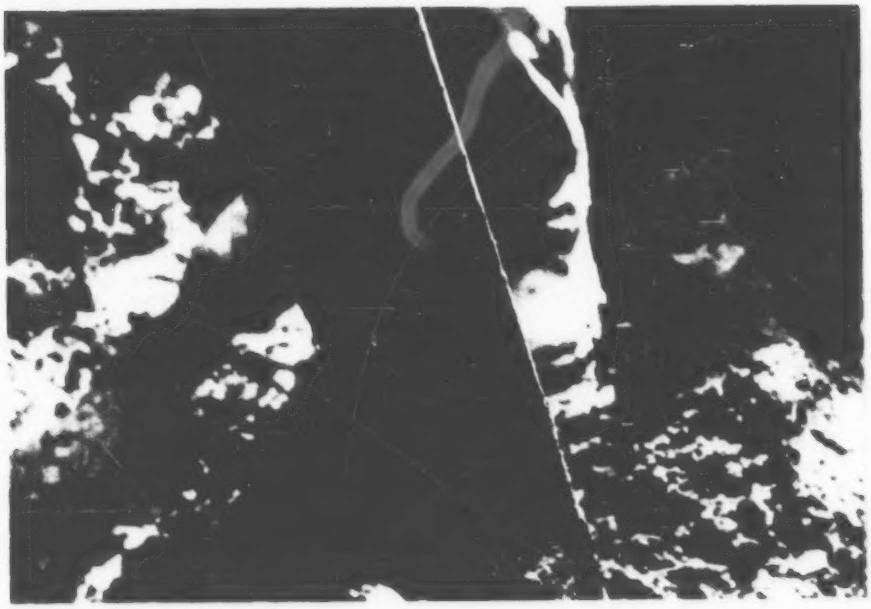


FIGURE A4

CIRCUIT B5G - TOWER 50

FIGURE A5

CIRCUIT B5G - TOWER 50

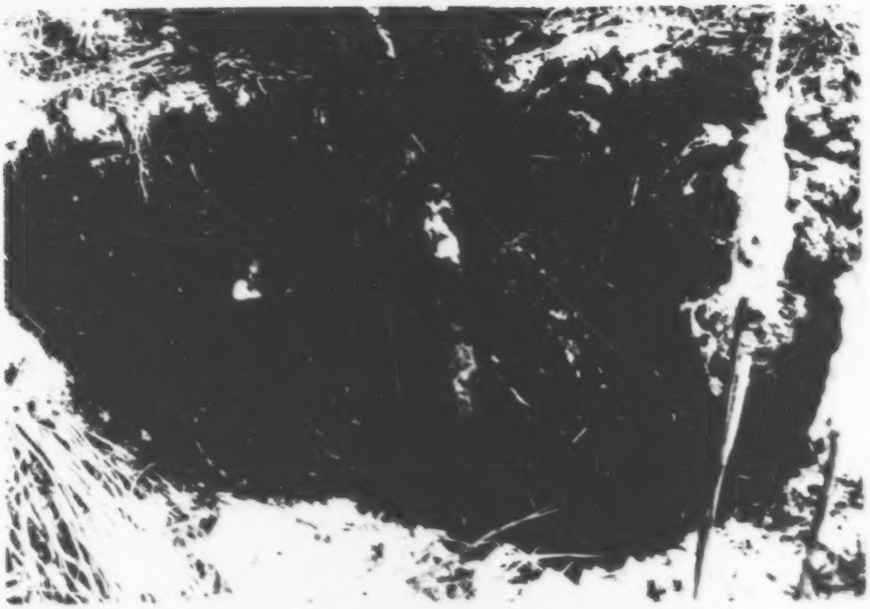


FIGURE A6

CIRCUIT B5G - TOWER 96

FIGURE A7

CIRCUIT B5G - TOWER 96

FIGURE A8

CIRCUIT B5G - TOWER 140

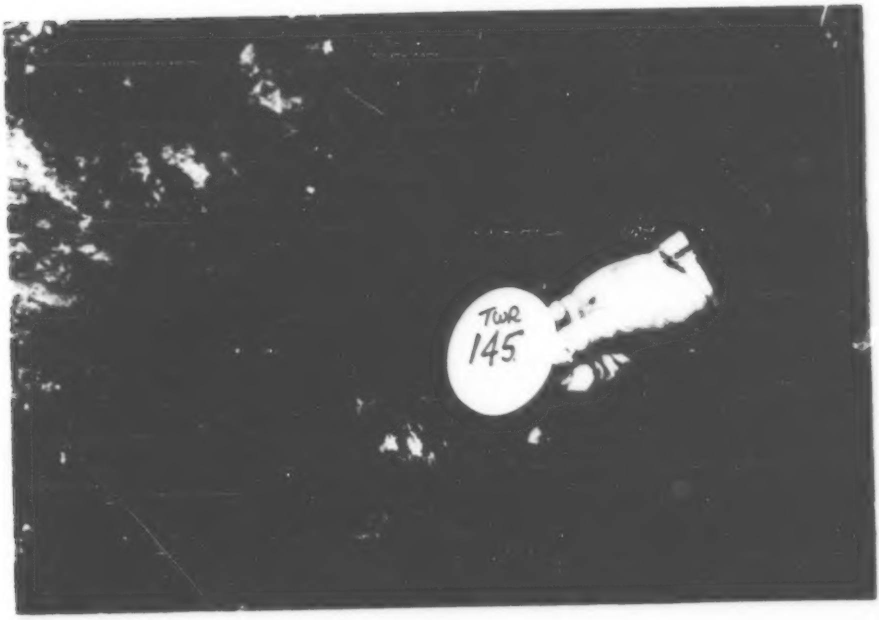


FIGURE A9

CIRCUIT B5G - TOWER 145

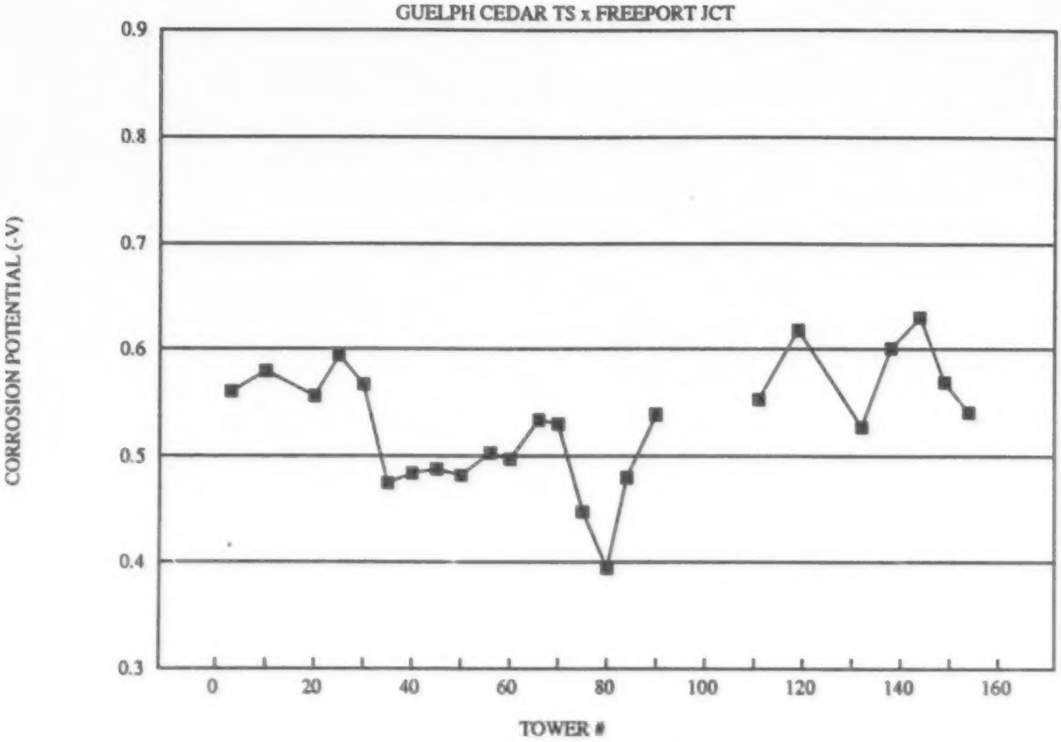


FIGURE A10a

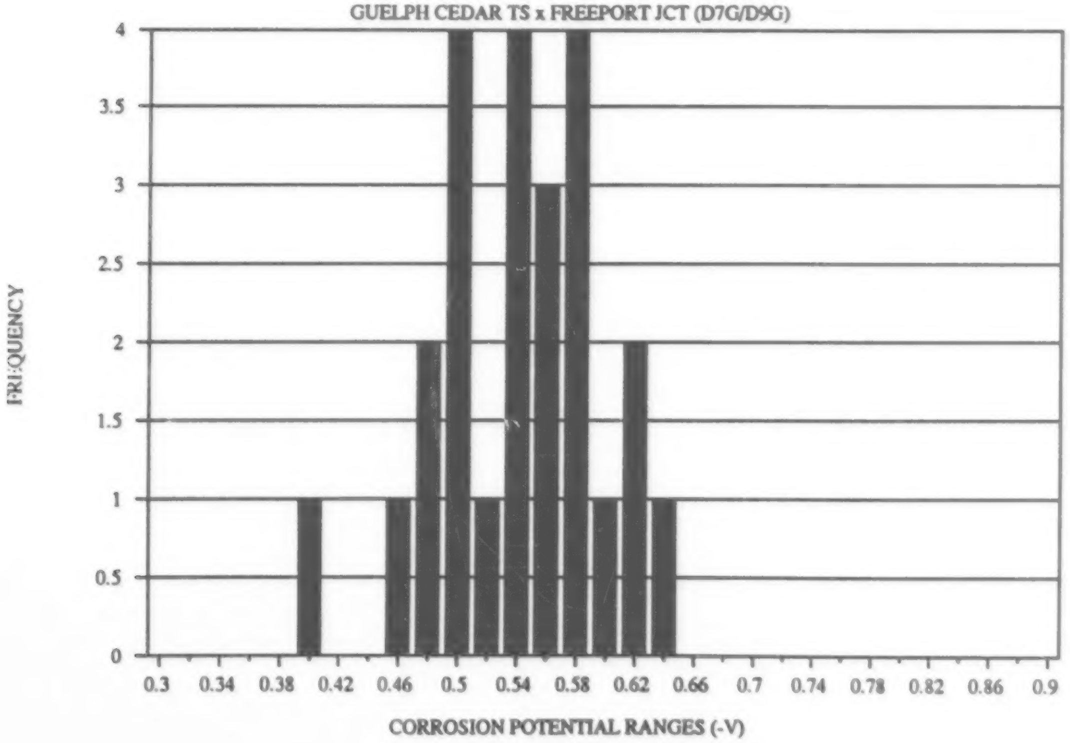


FIGURE A10b

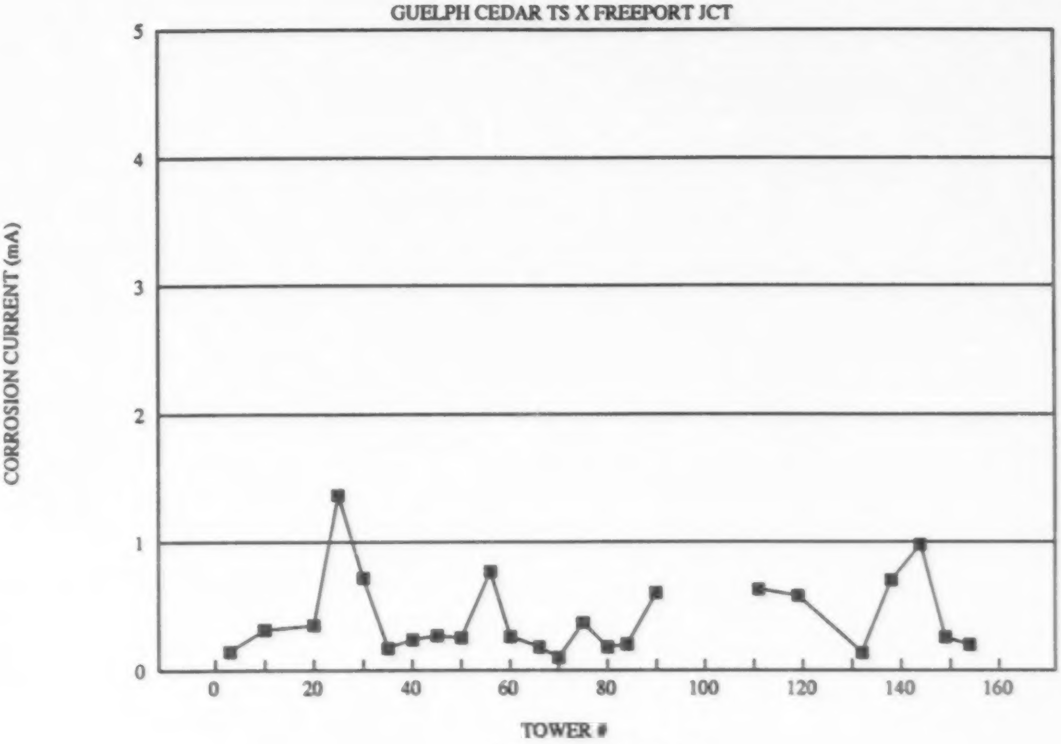


FIGURE A11a

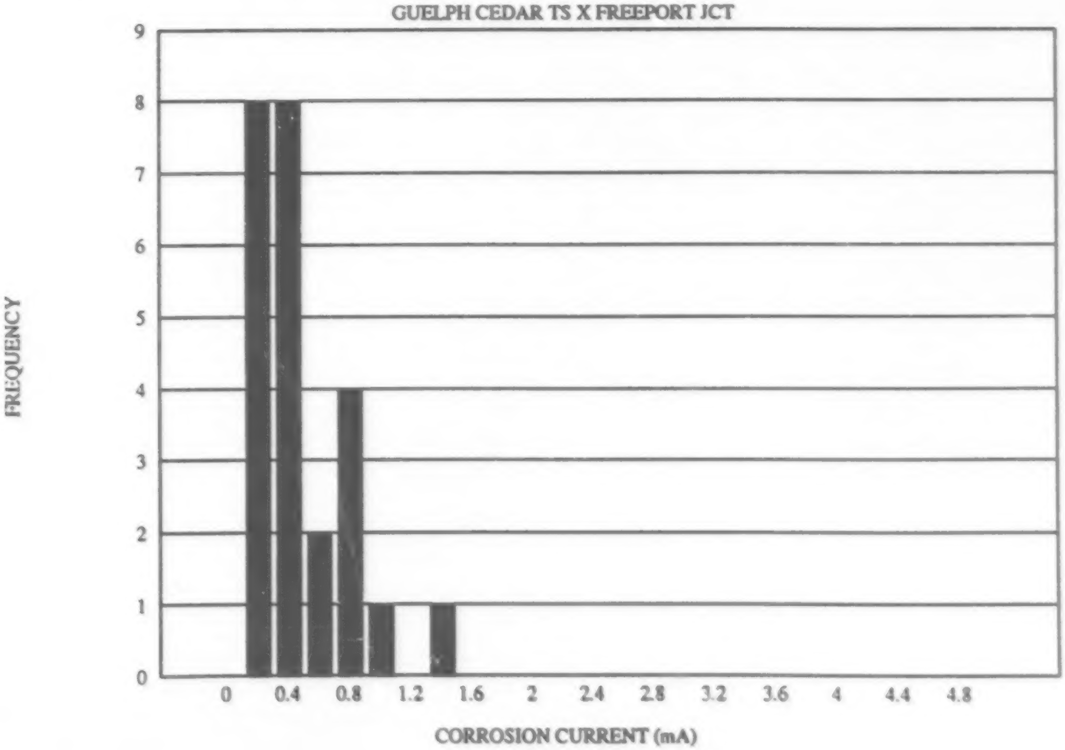


FIGURE A11b

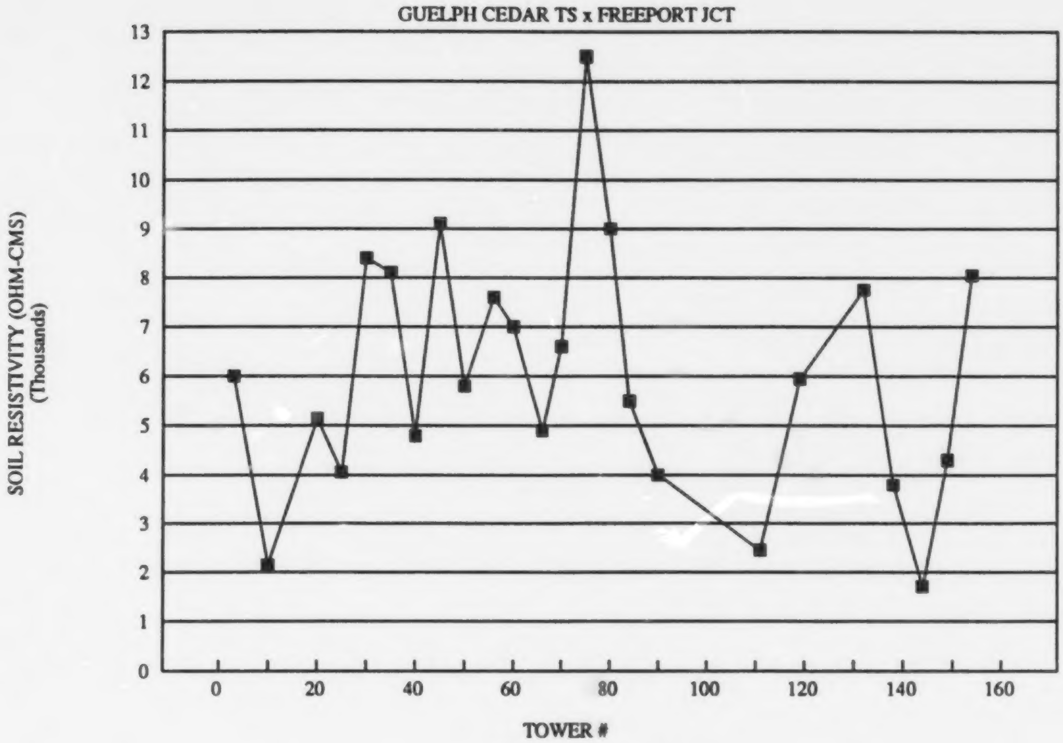


FIGURE A12a

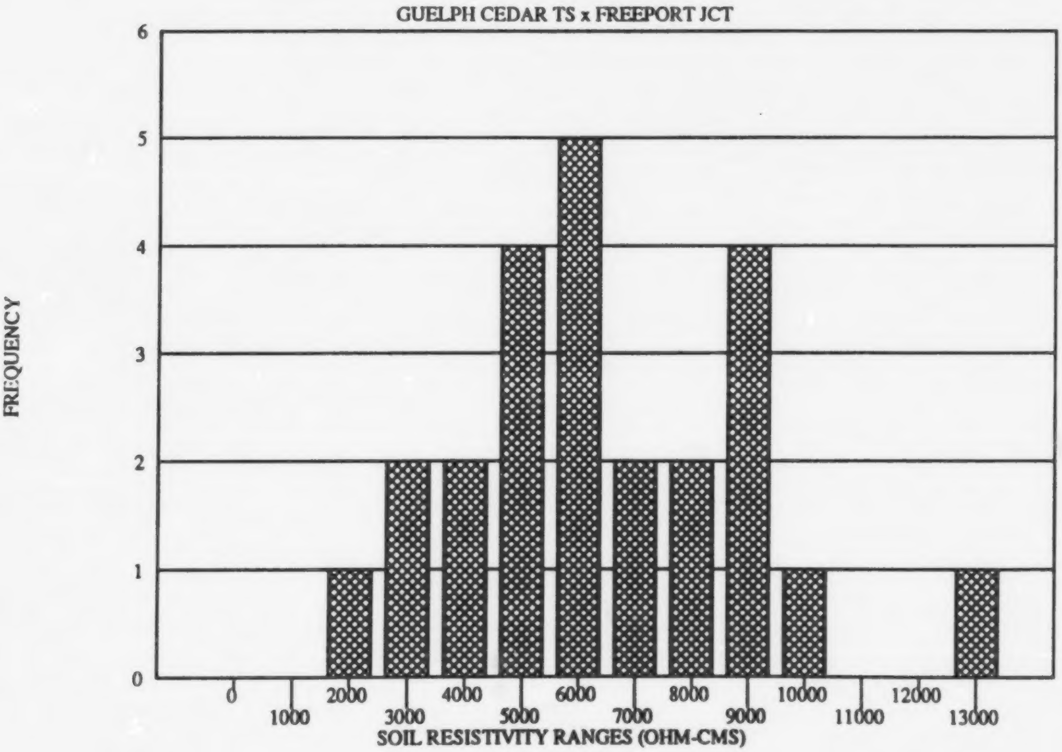


FIGURE A12b

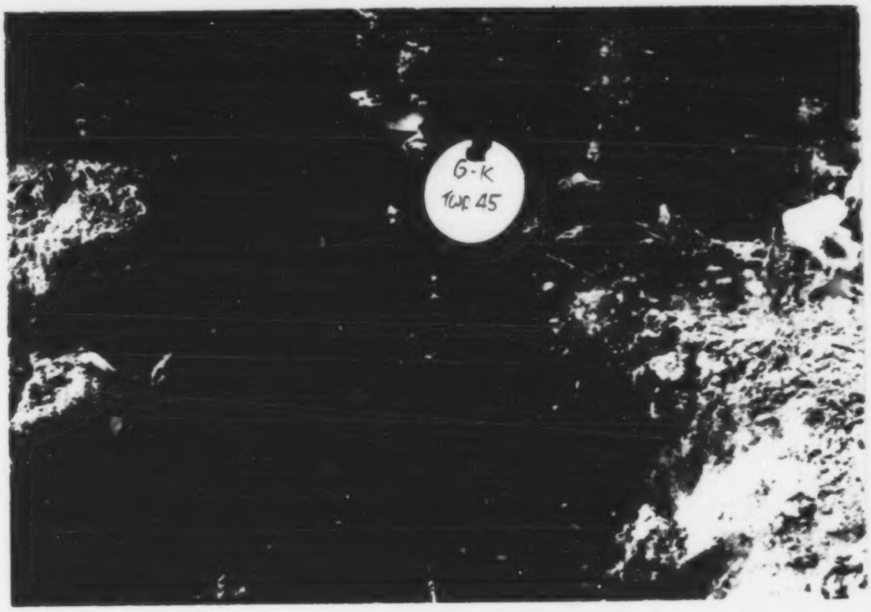


FIGURE A13

CIRCUIT D7G - TOWER 45

FIGURE A14

CIRCUIT D7G - TOWER 45

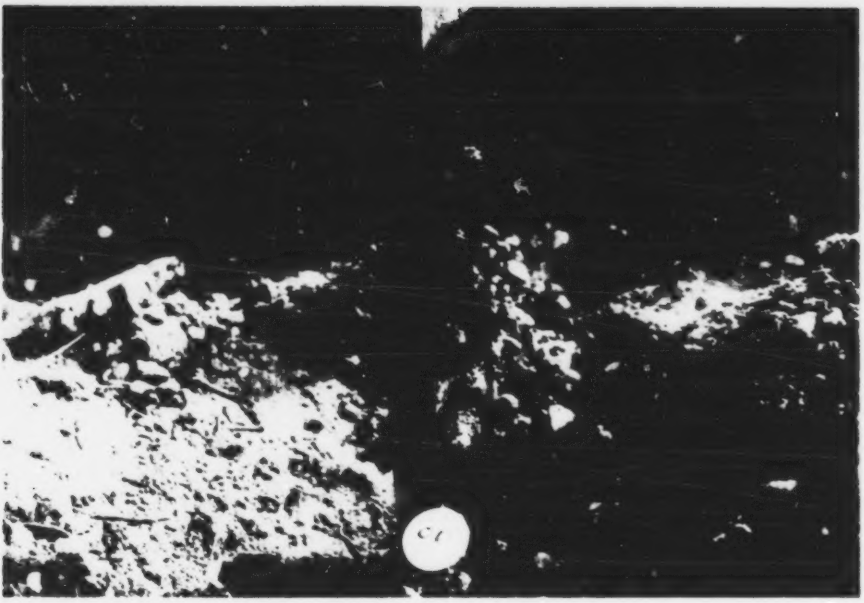


FIGURE A15

CIRCUIT D7G - TOWER 80

FIGURE A16

CIRCUIT D7G - TOWER 80

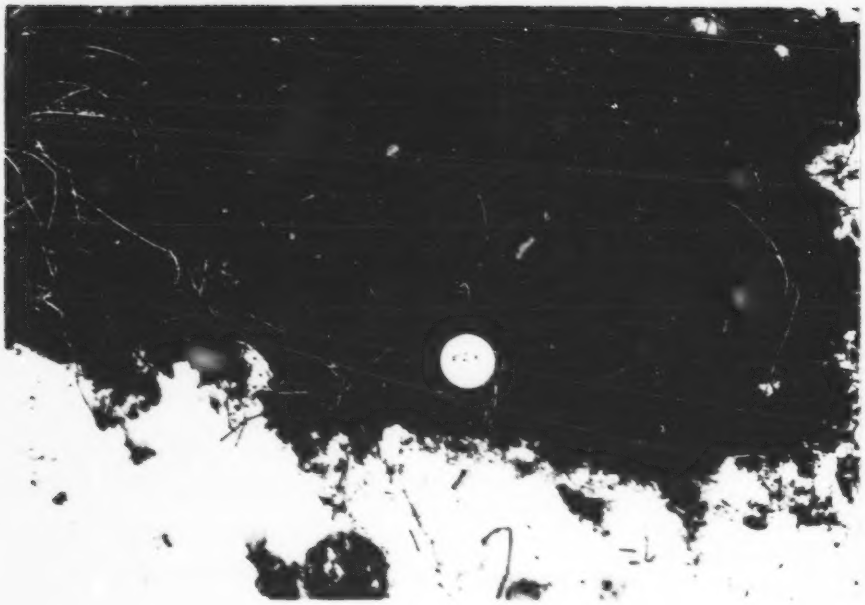


FIGURE A17

CIRCUIT D7G - TOWER 80
REINFORCING ANGLE ON OUTSIDE OF LEG

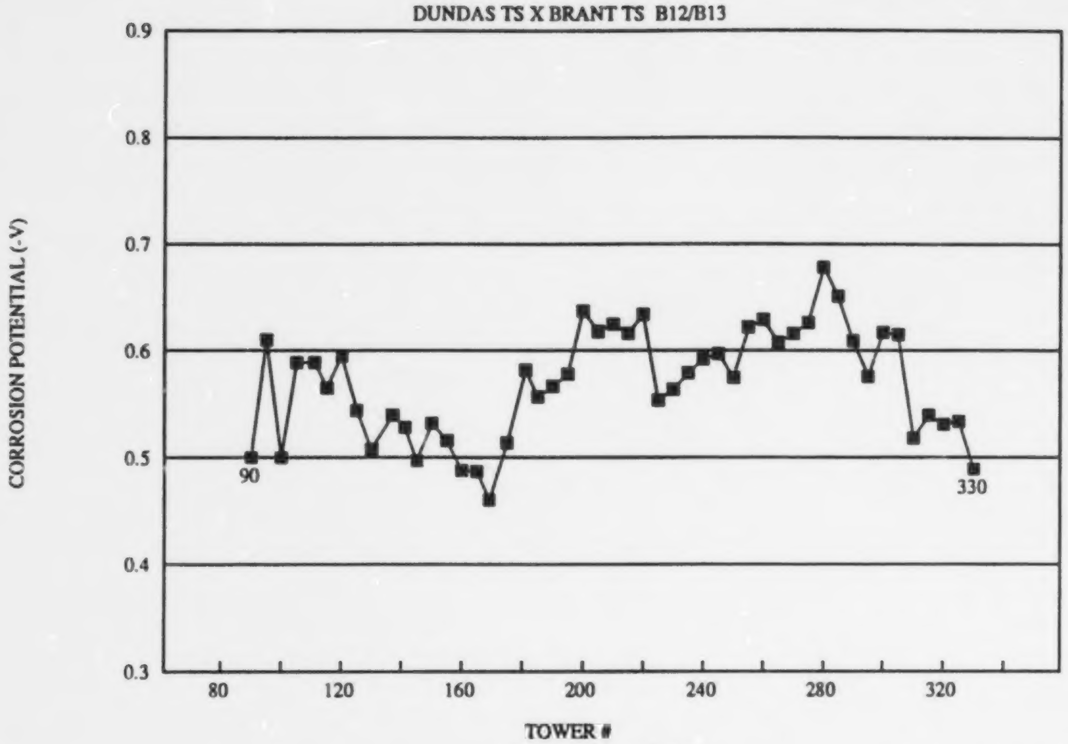


FIGURE A18a

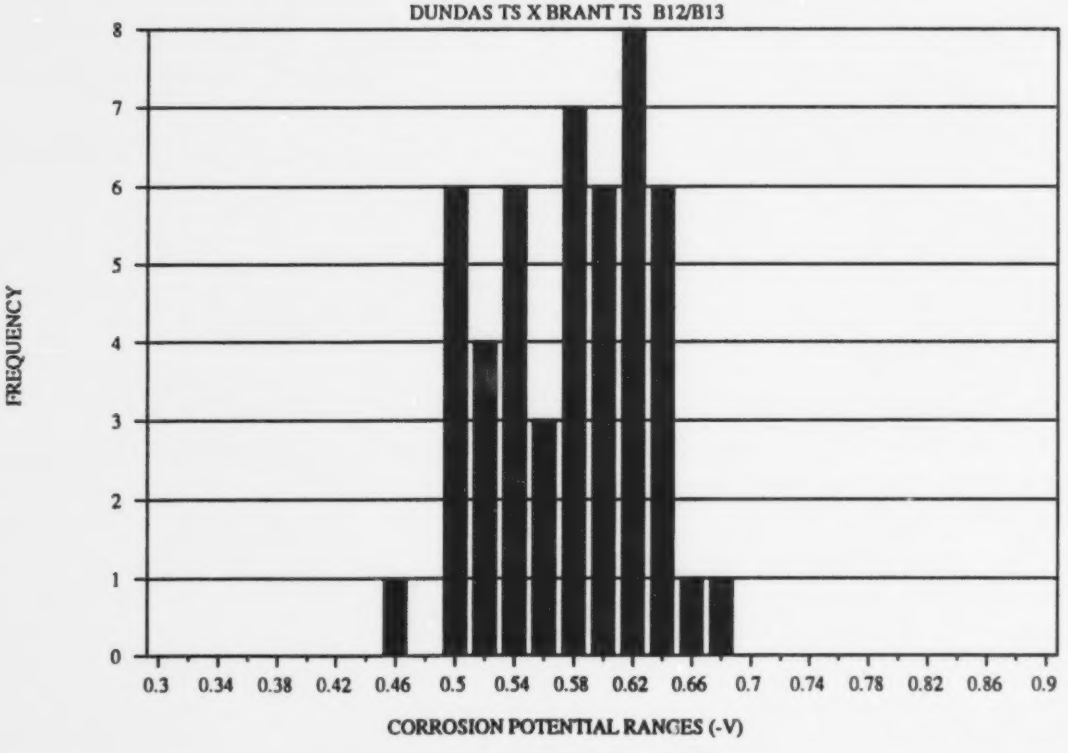


FIGURE A18b

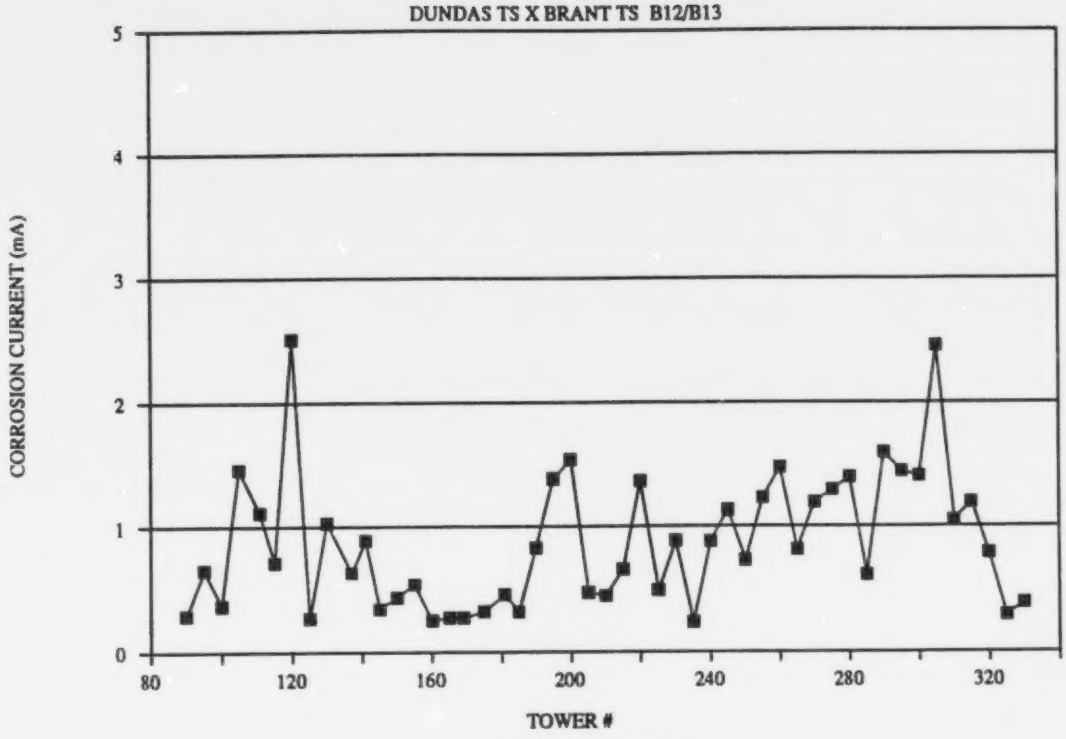


FIGURE A19a

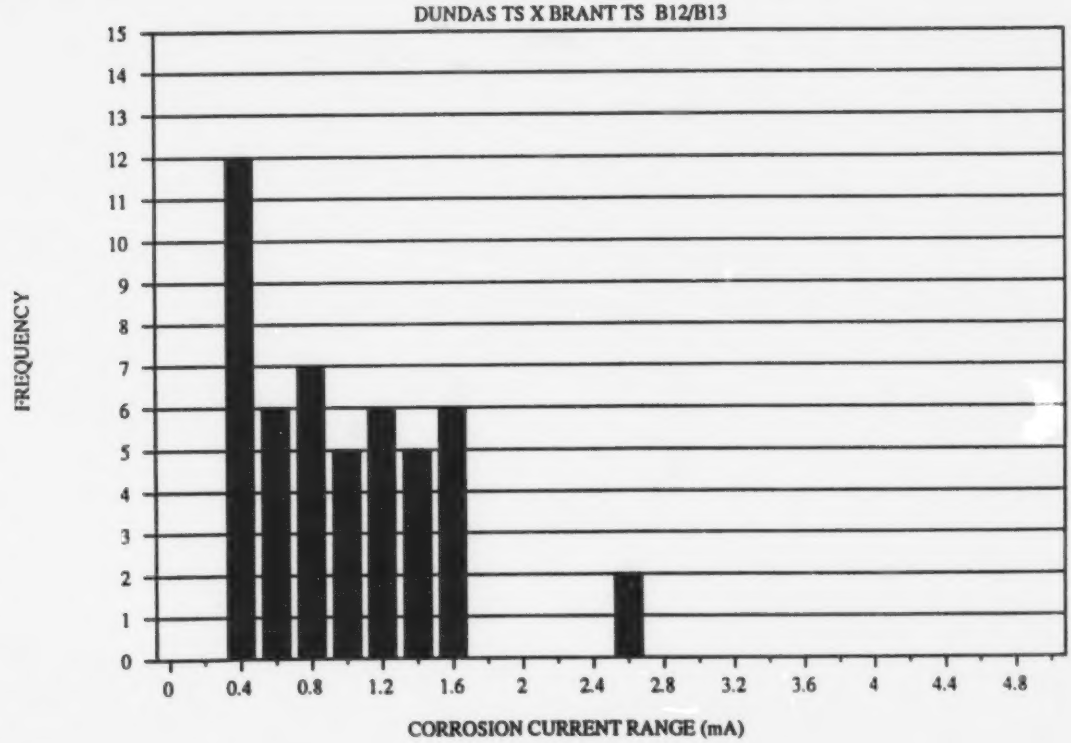


FIGURE A19b

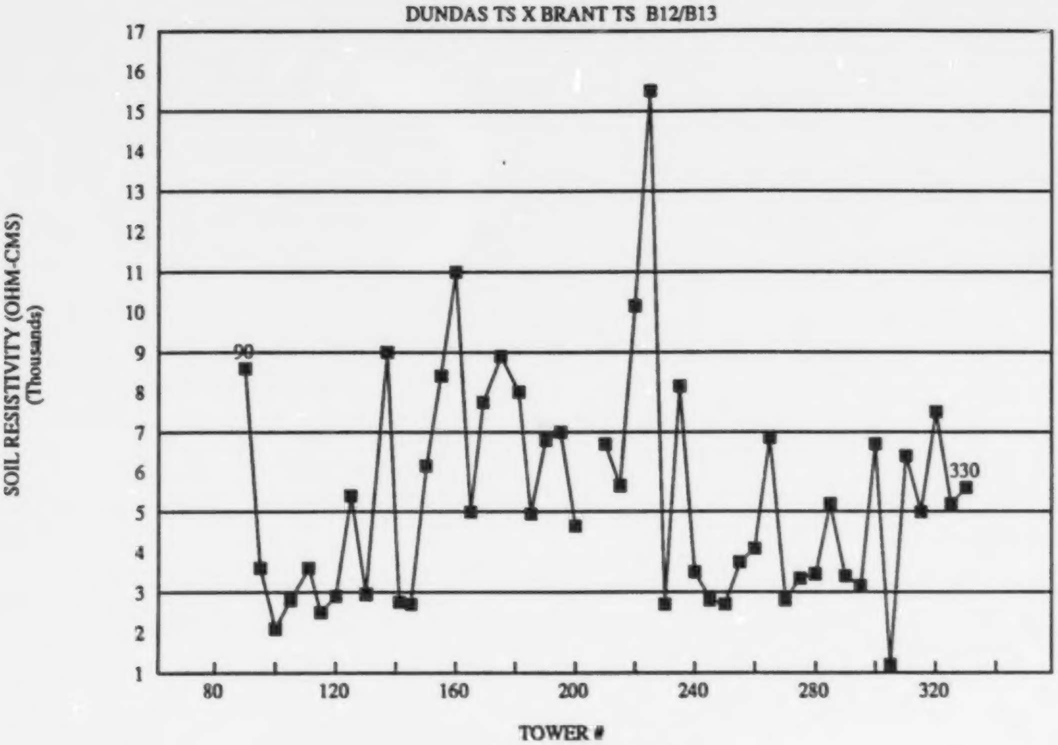


FIGURE A20a

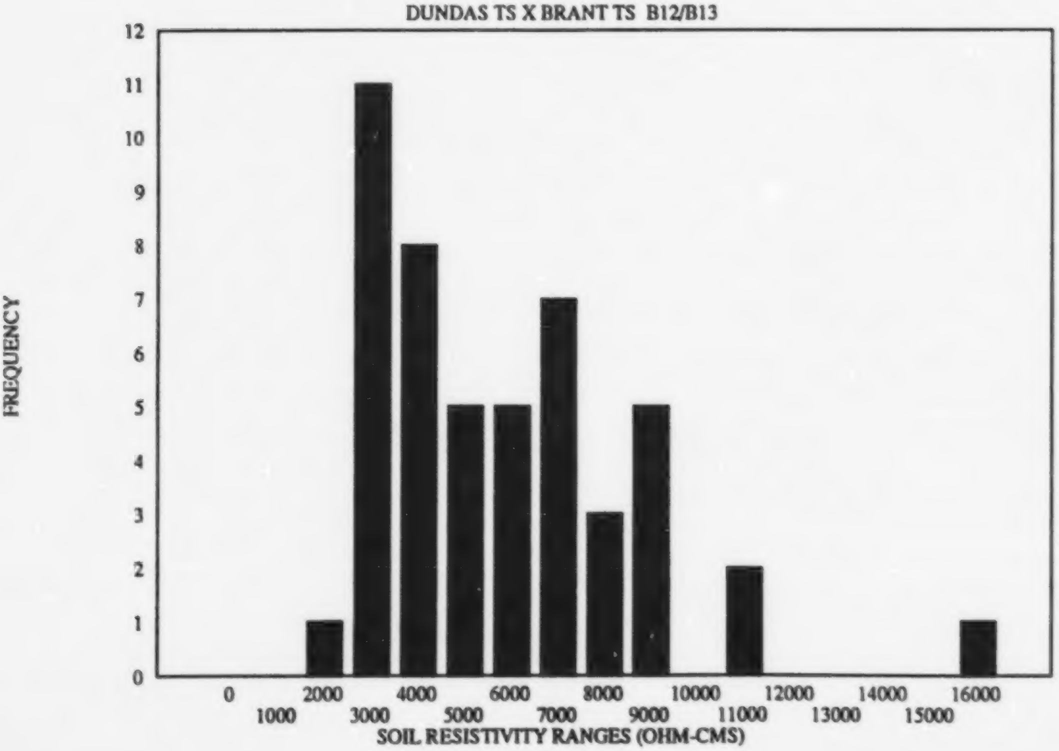


FIGURE A20b

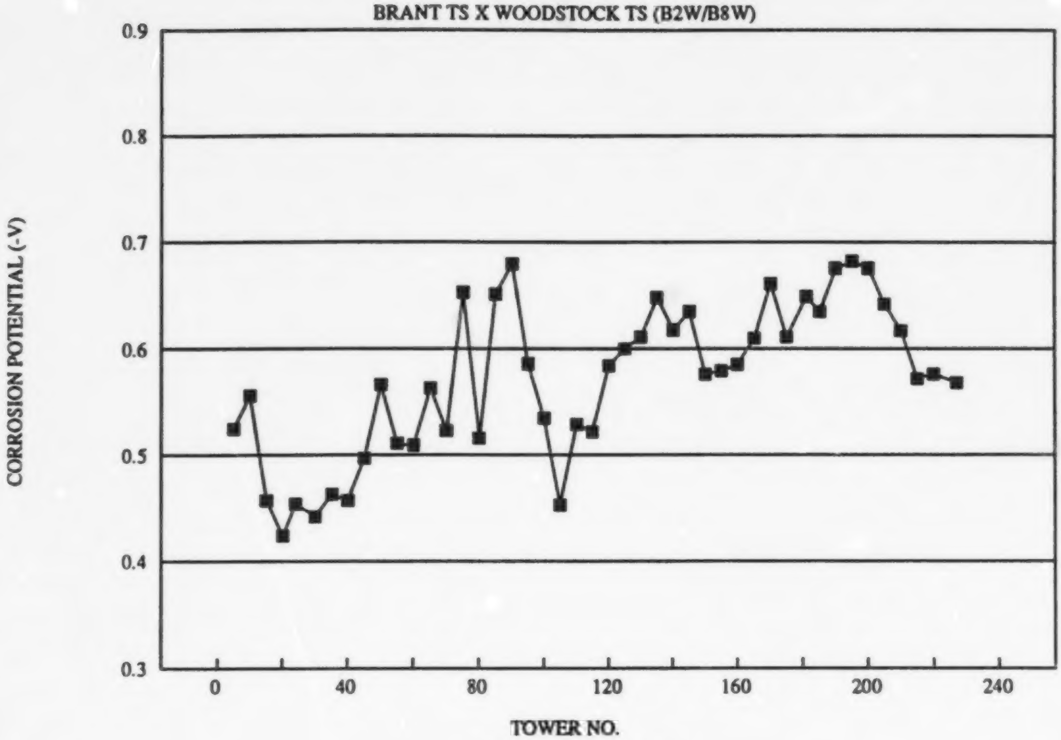


FIGURE A21a

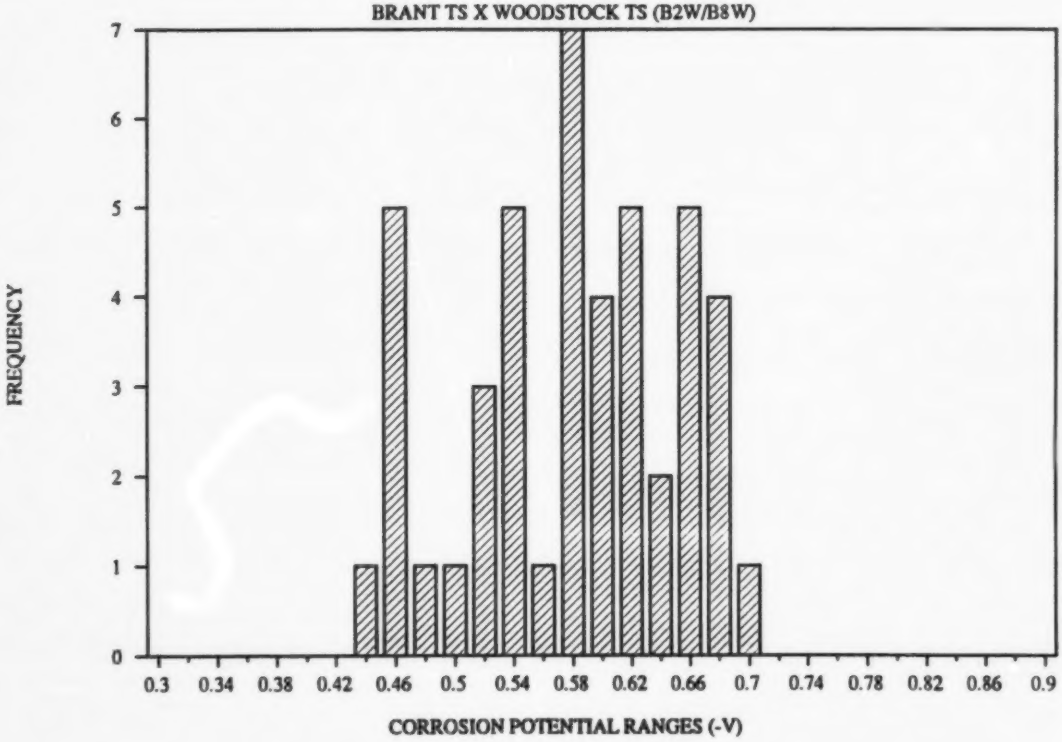


FIGURE A21b

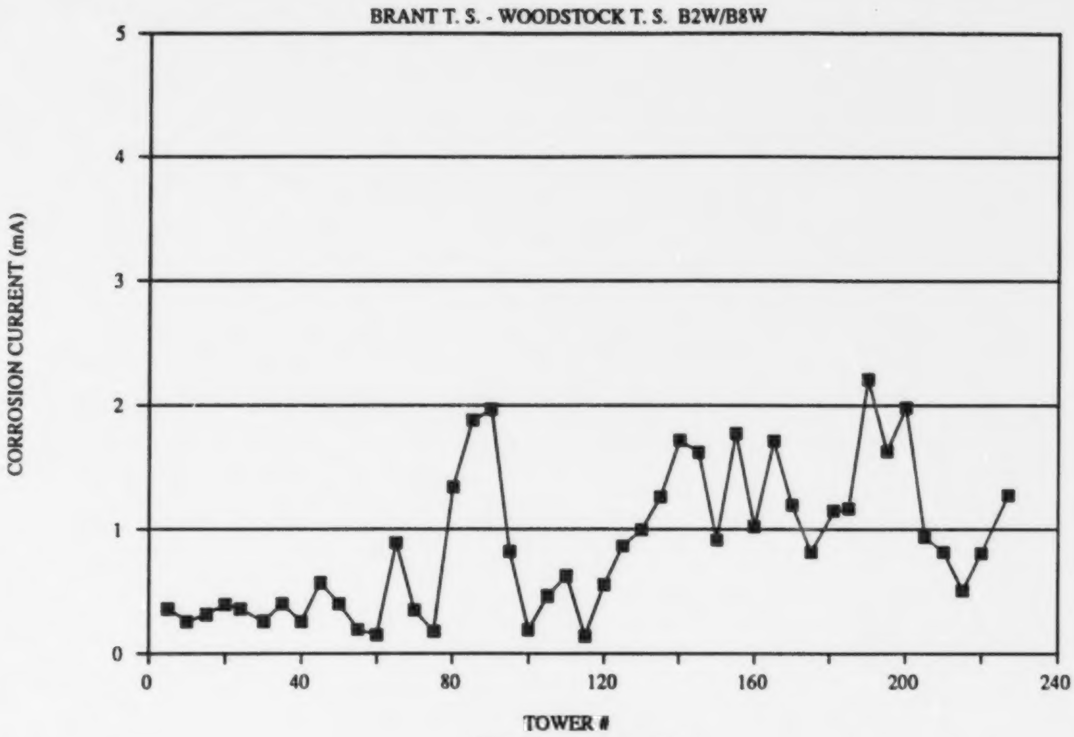


FIGURE A22a

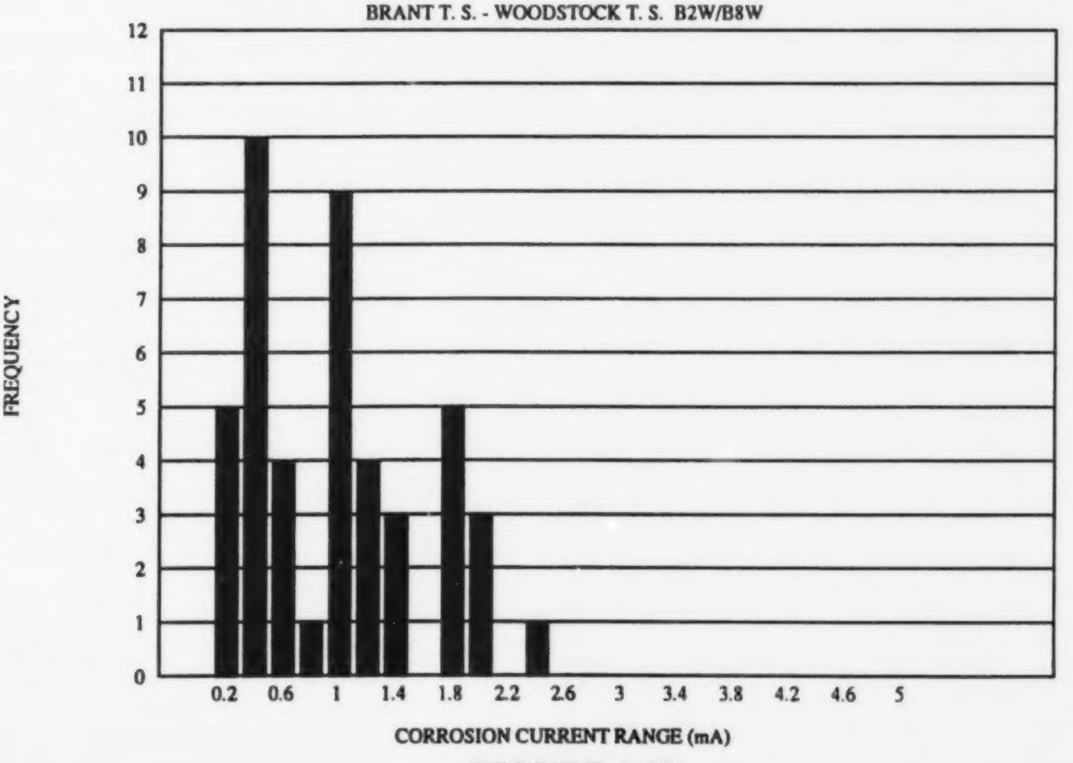


FIGURE A22b

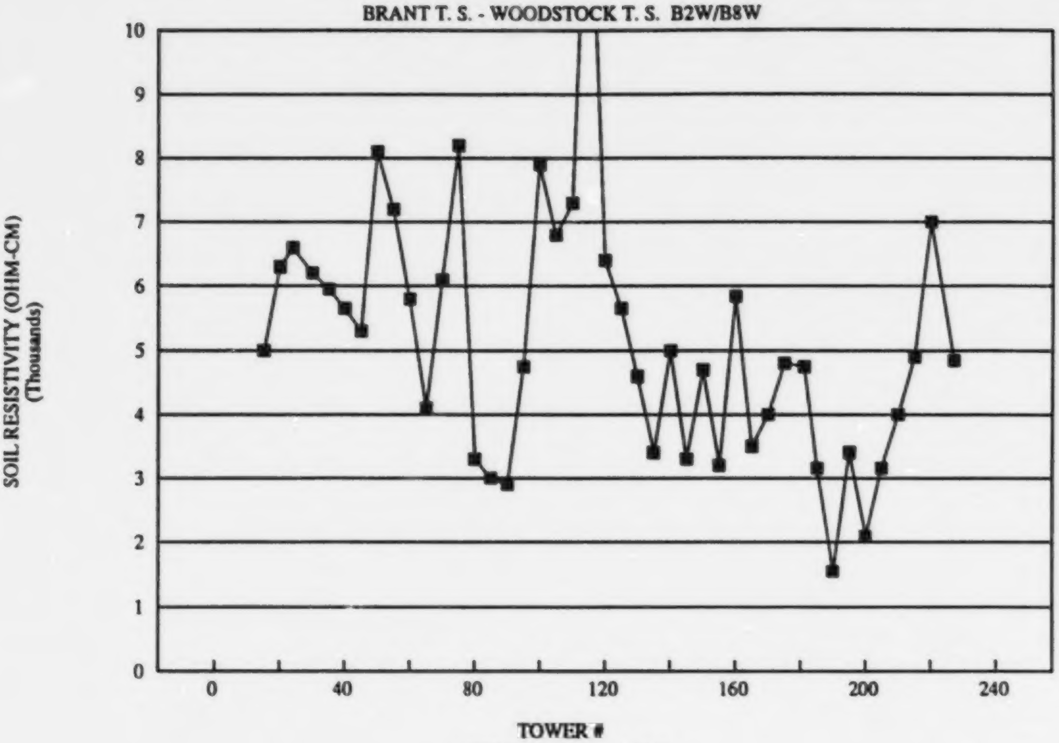


FIGURE A23a

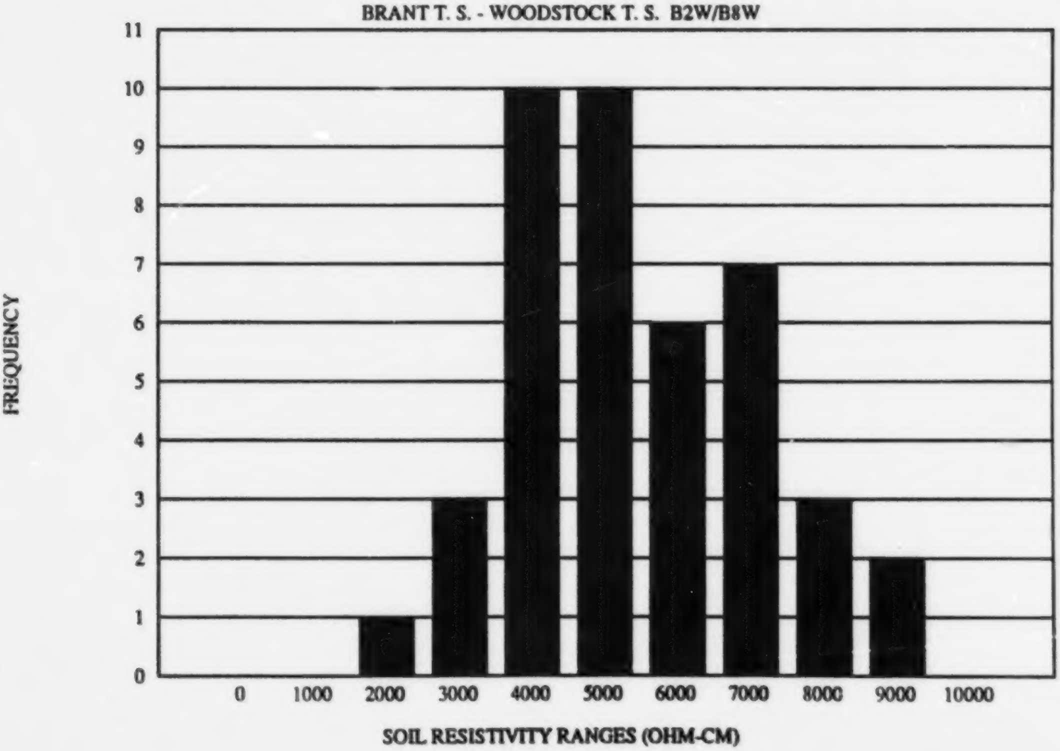


FIGURE A23b

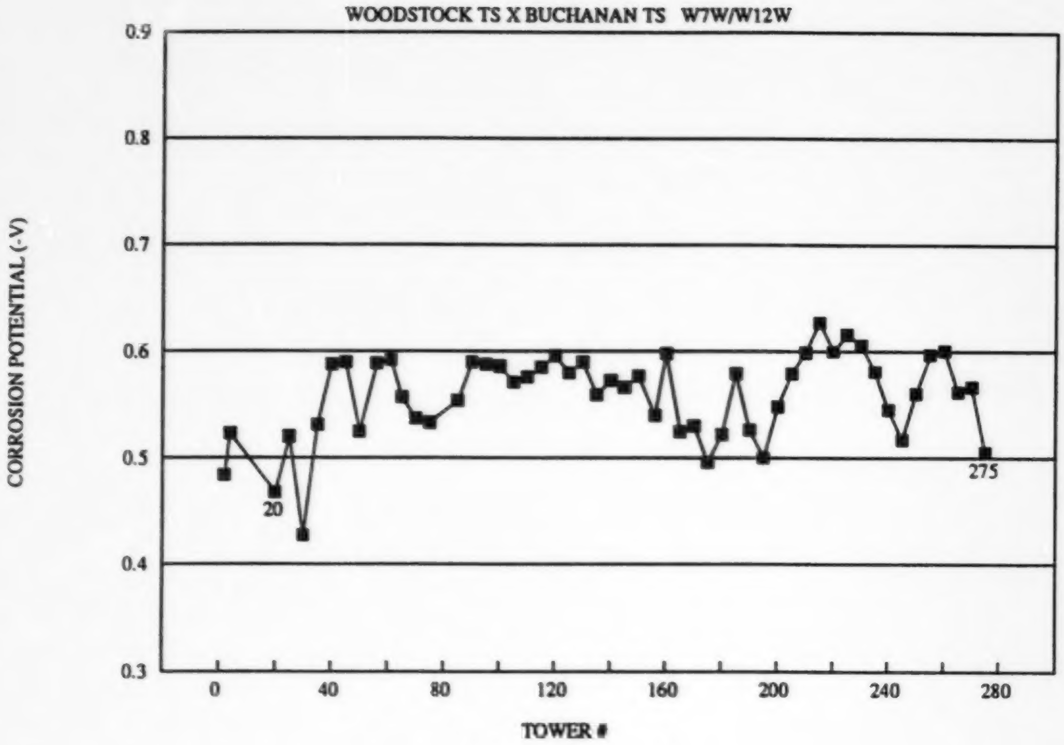


FIGURE A24a

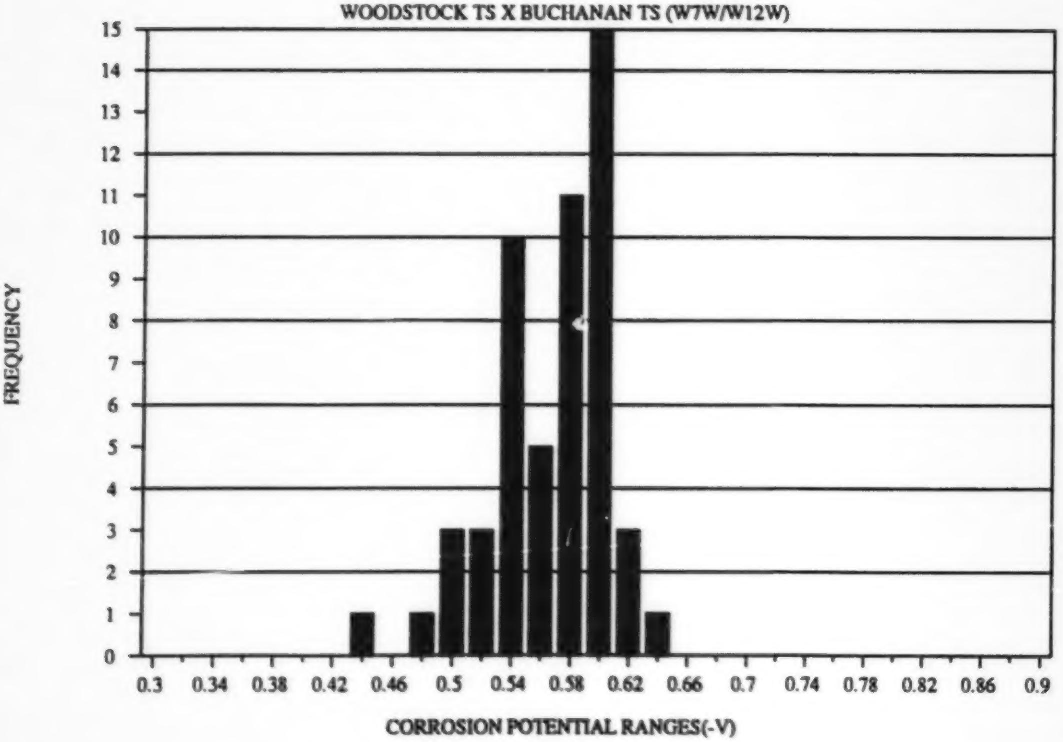


FIGURE A24b

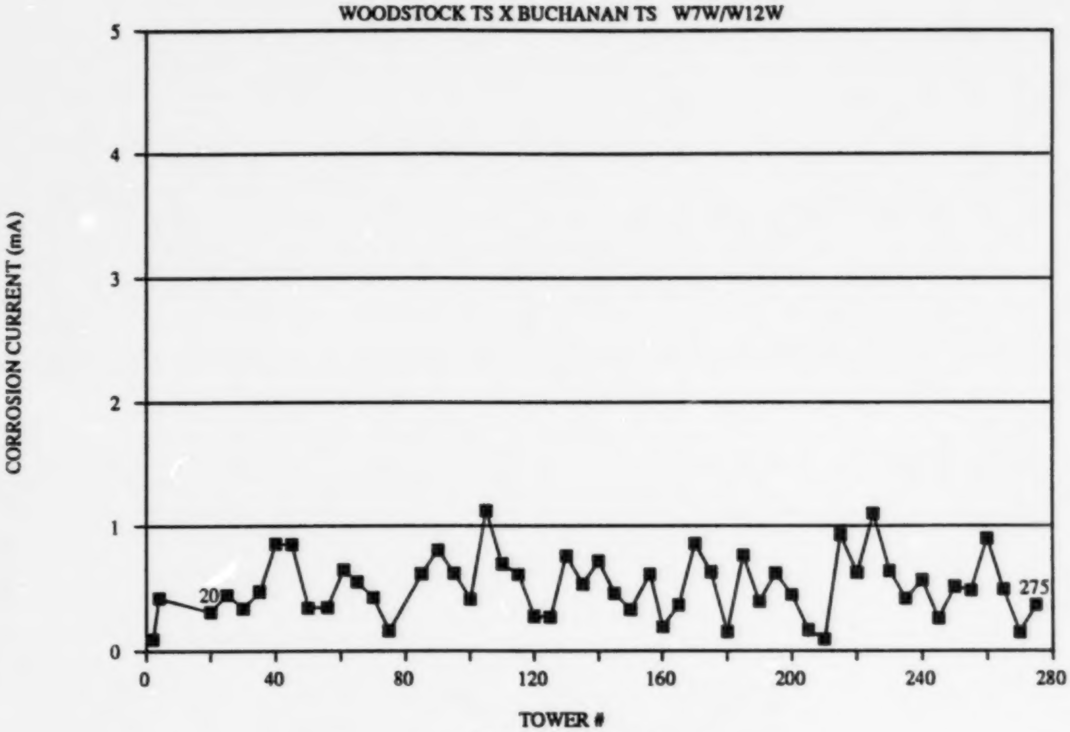


FIGURE A25a

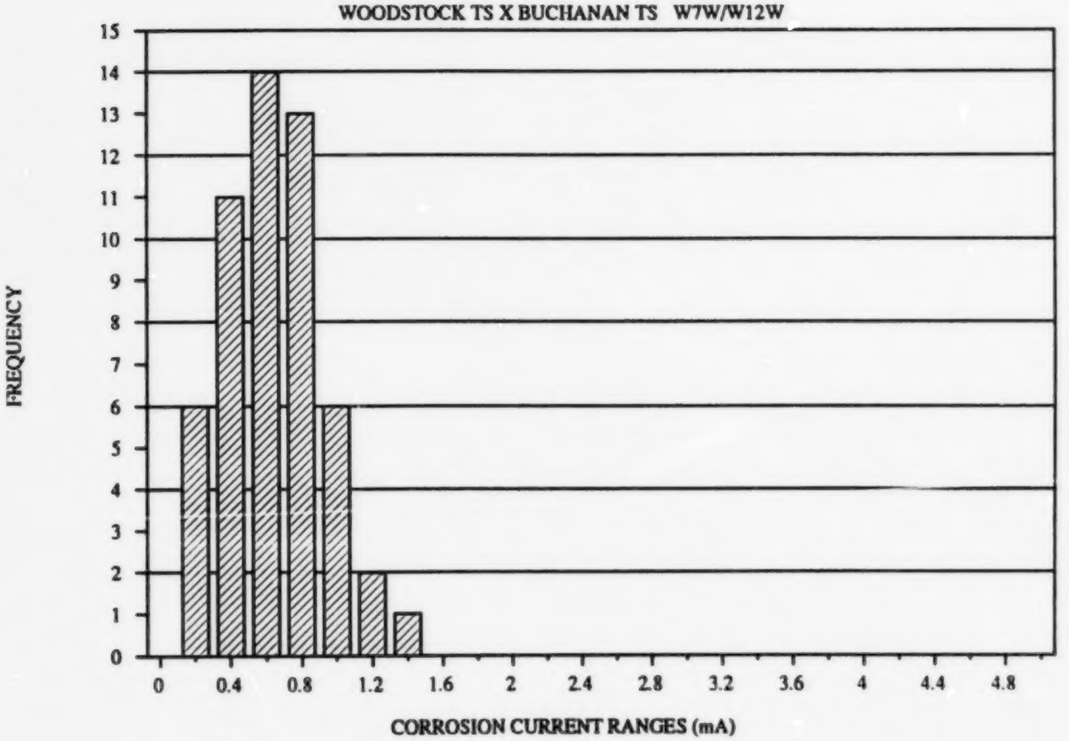


FIGURE A25b

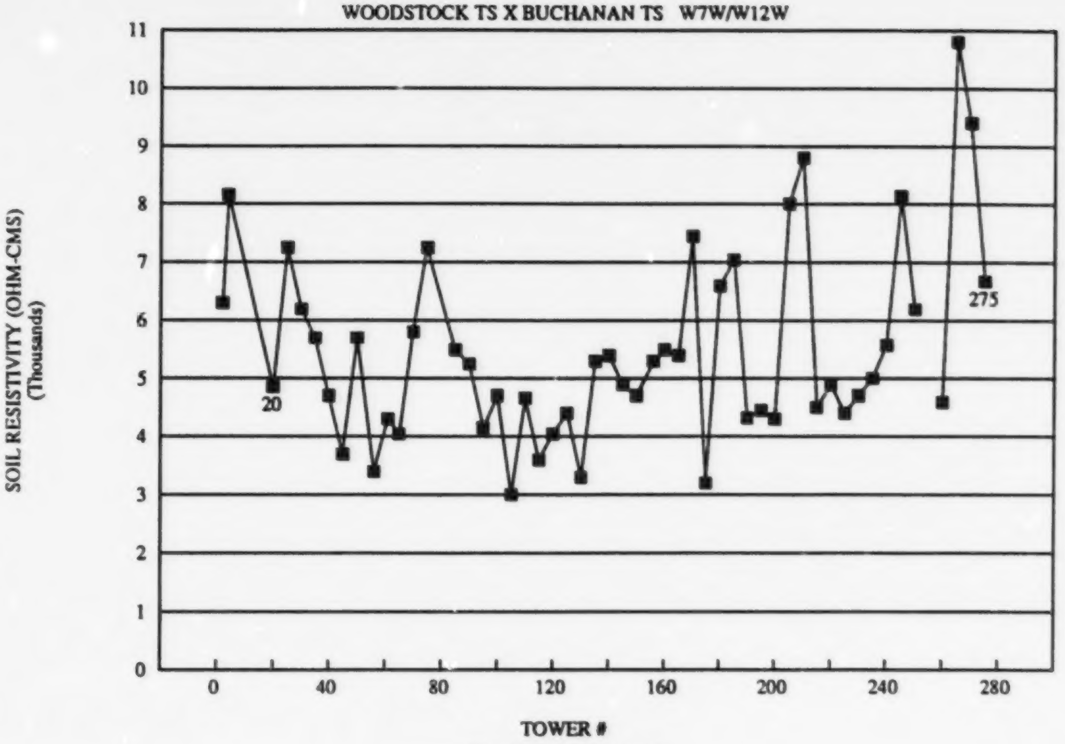


FIGURE A26a

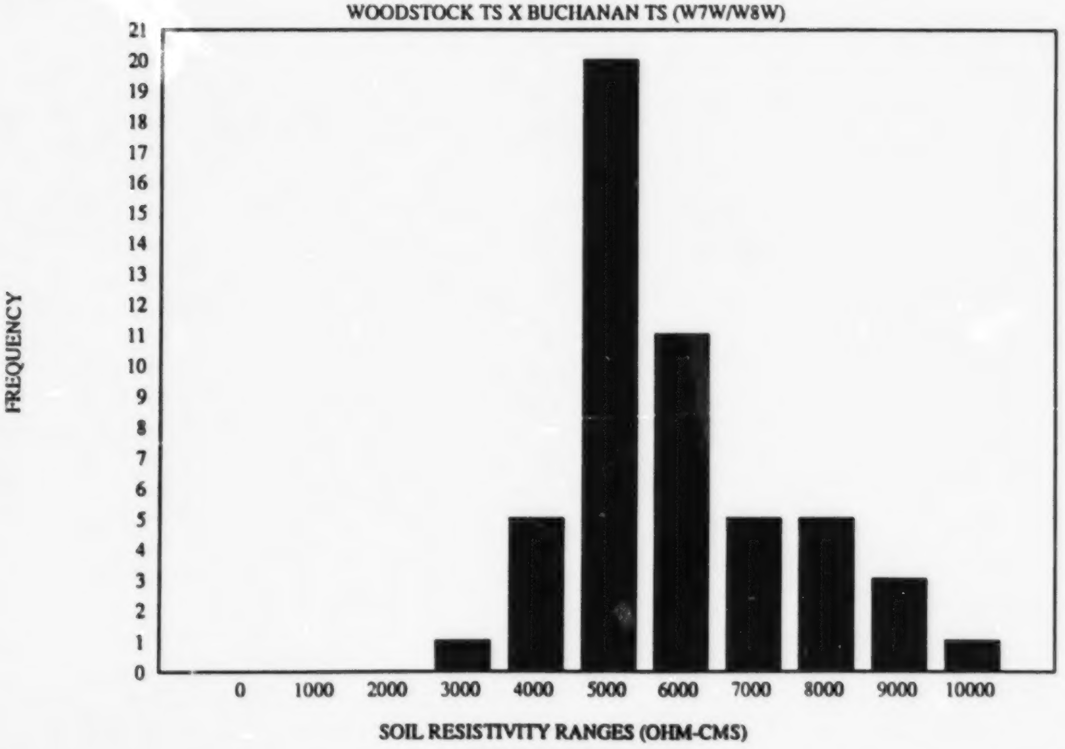


FIGURE A26b

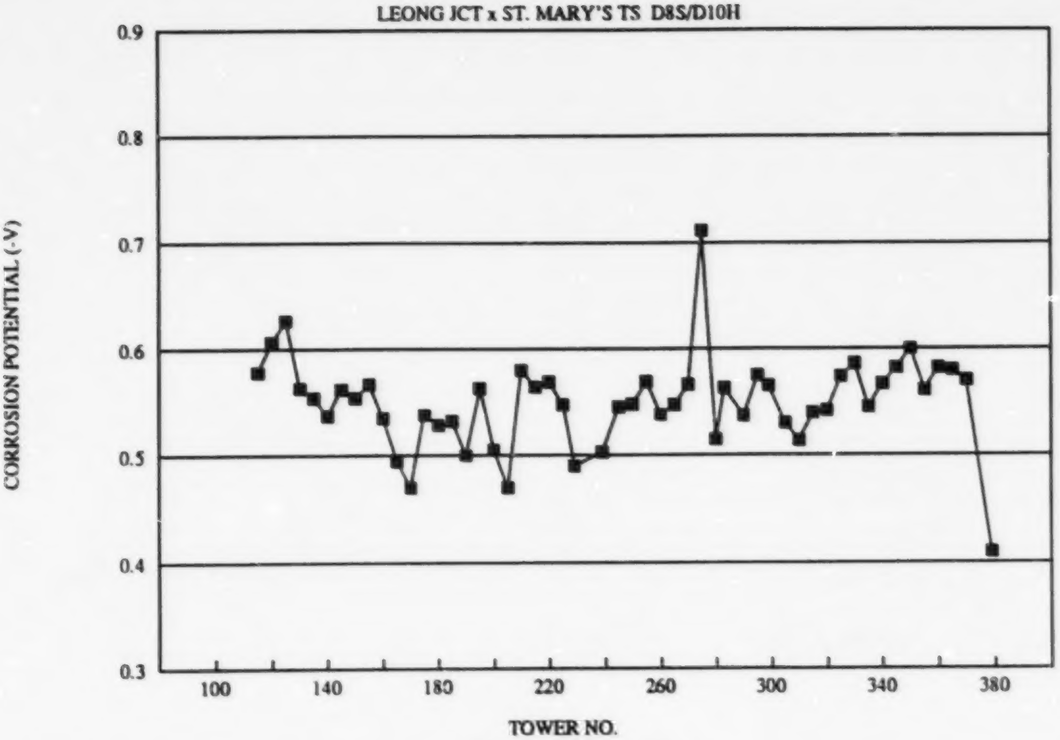


FIGURE A27a

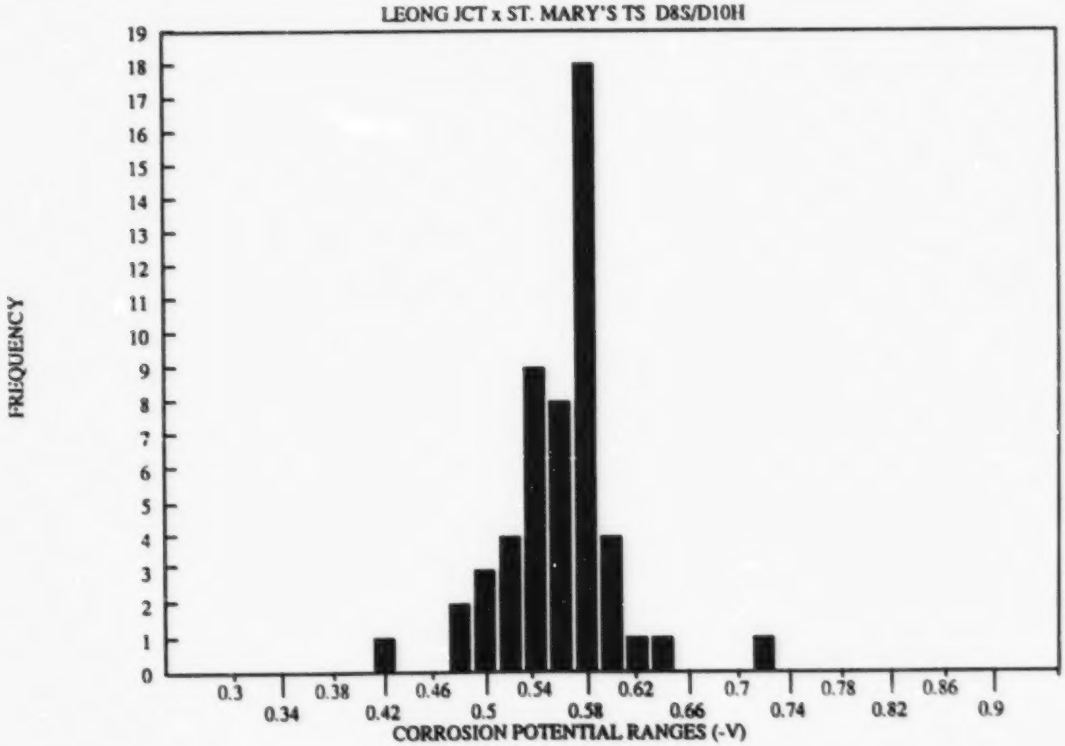


FIGURE A27b

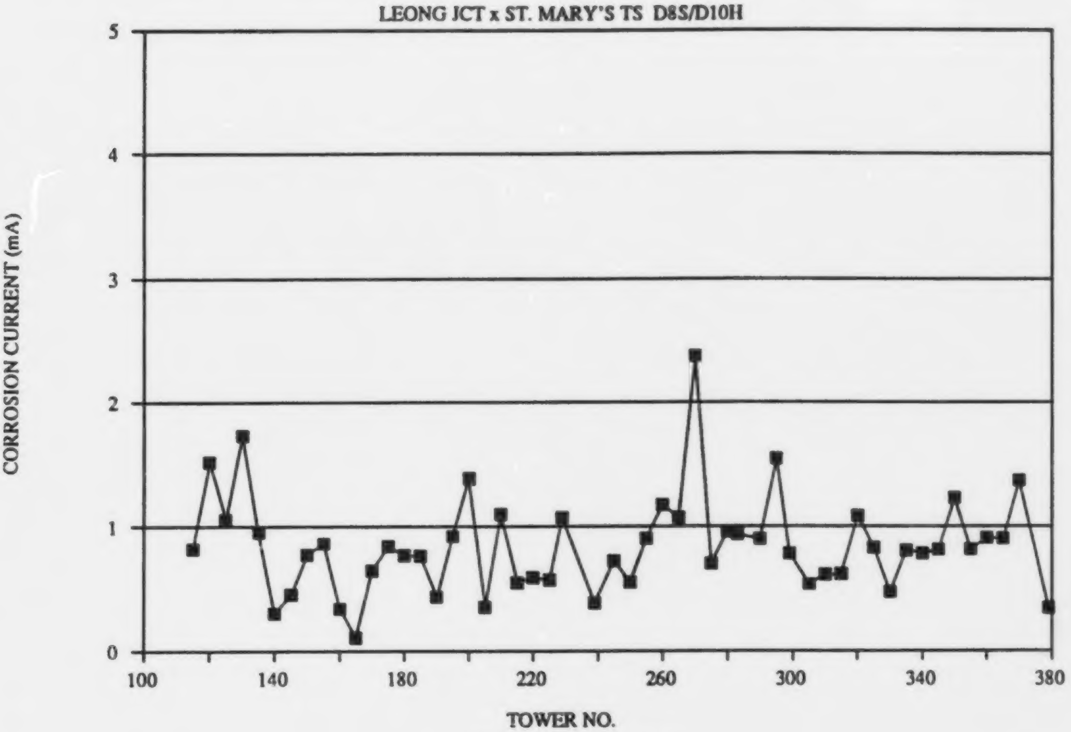


FIGURE A28a

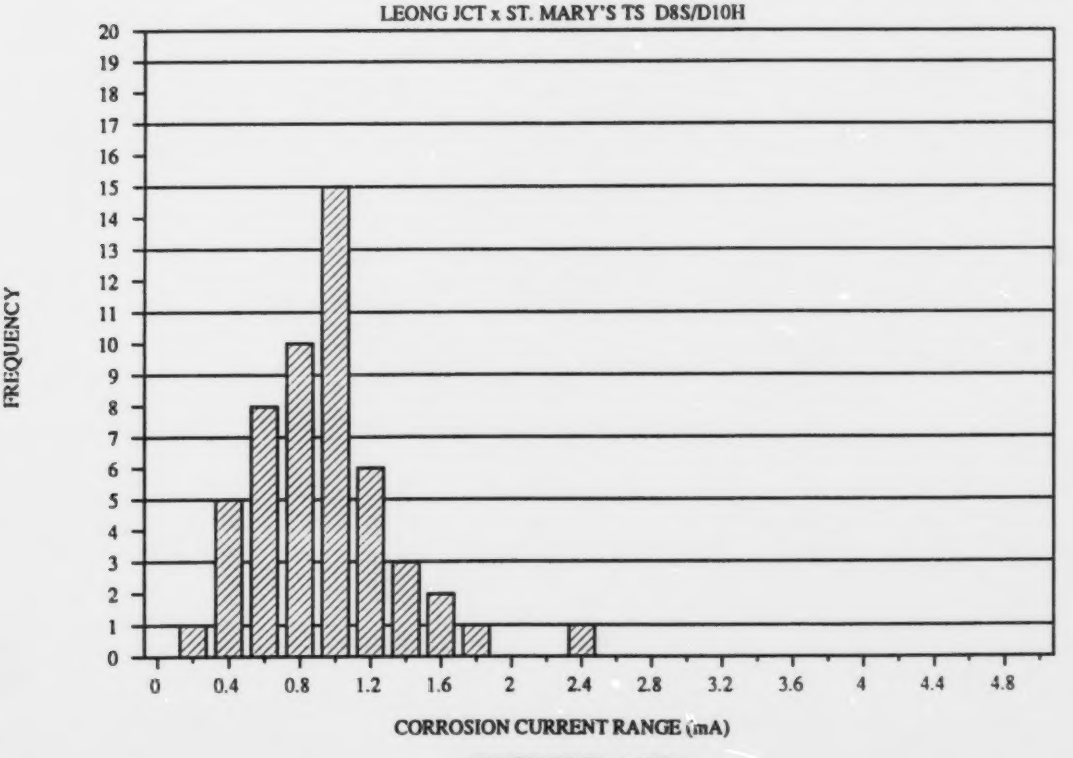


FIGURE A28b

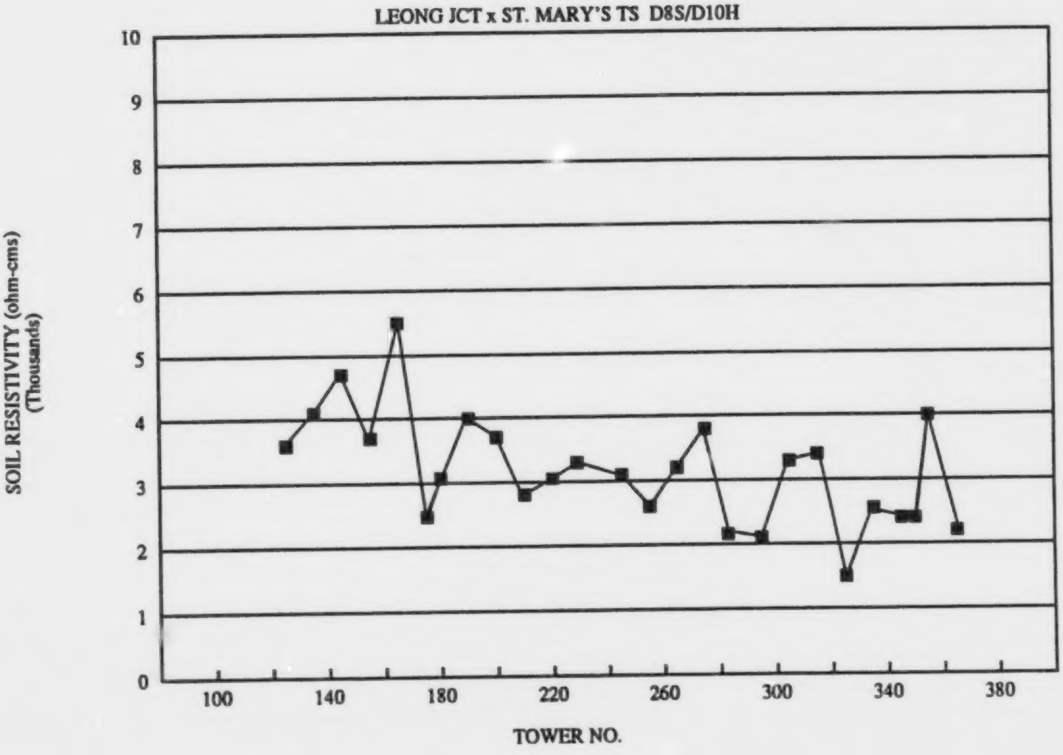

LEONG JCT x ST. MARY'S TS D8S/D10H
SOIL RESISTIVITY (ohm-cms)
(Thousands)
0
1
2
3
4
5
6
7
8
9
10
100
140
180
220
260
300
340
380
TOWER NO.

FIGURE A29

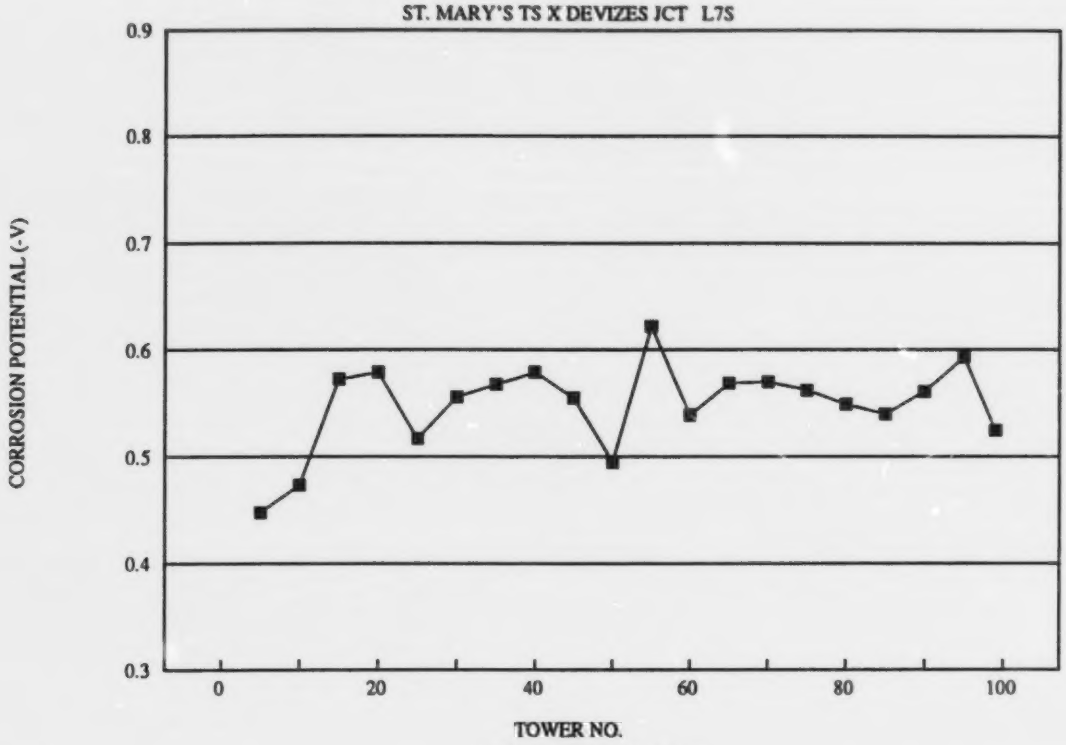


FIGURE A30a

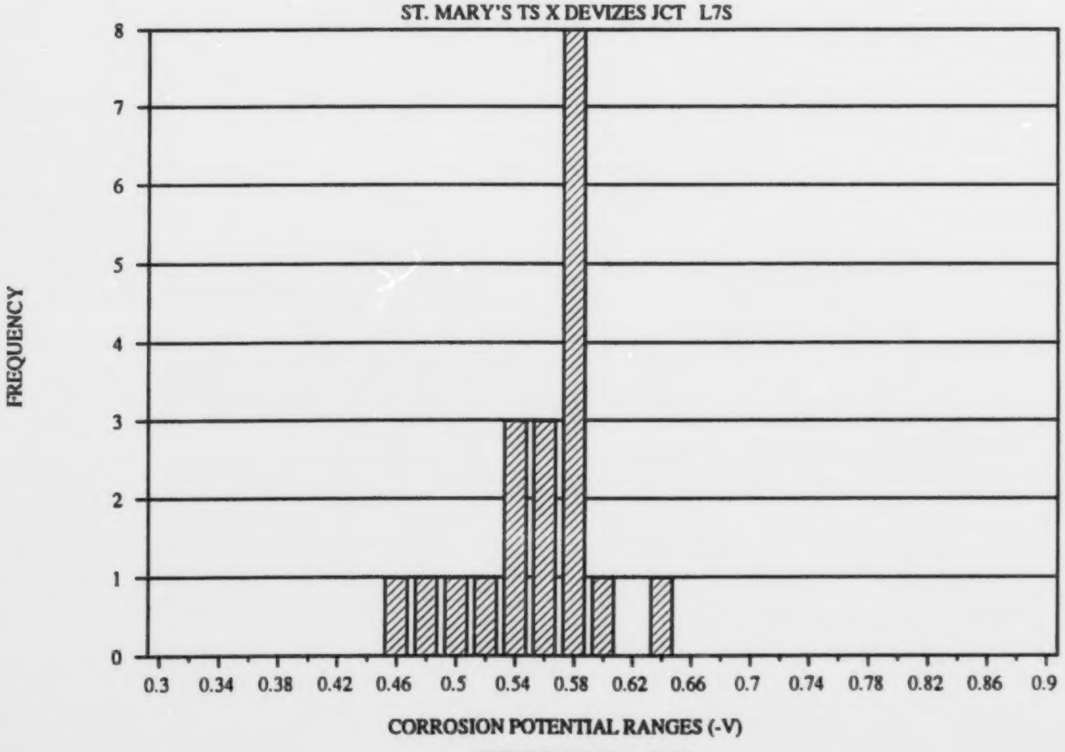


FIGURE A30b

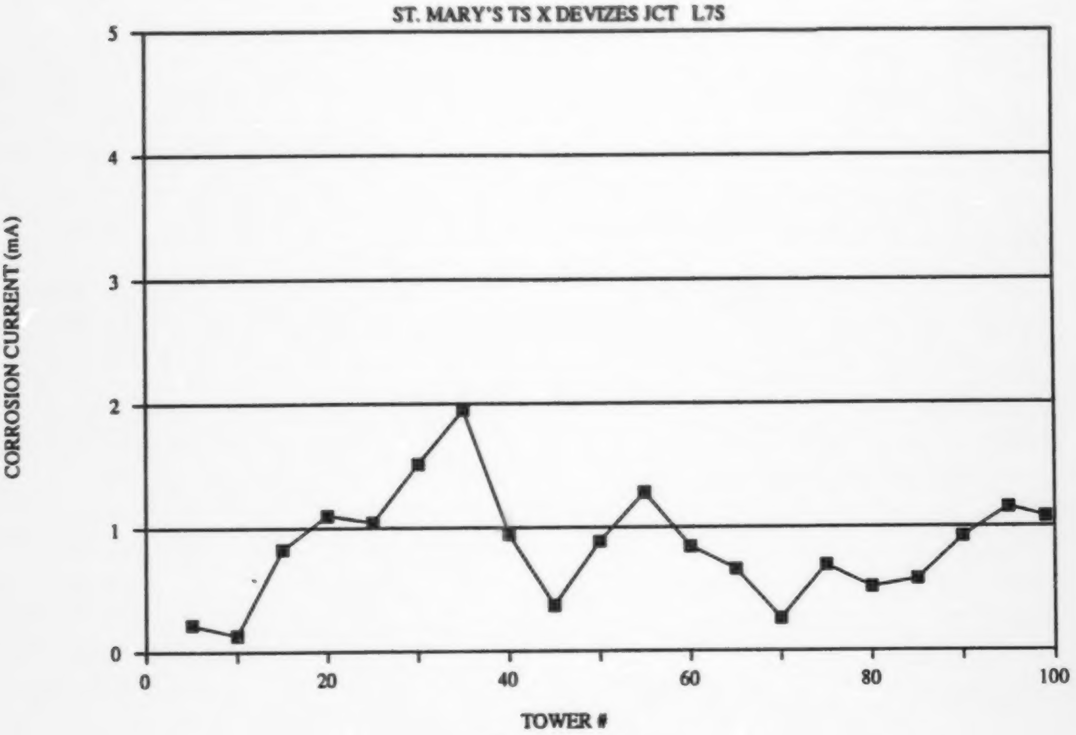


FIGURE A31a

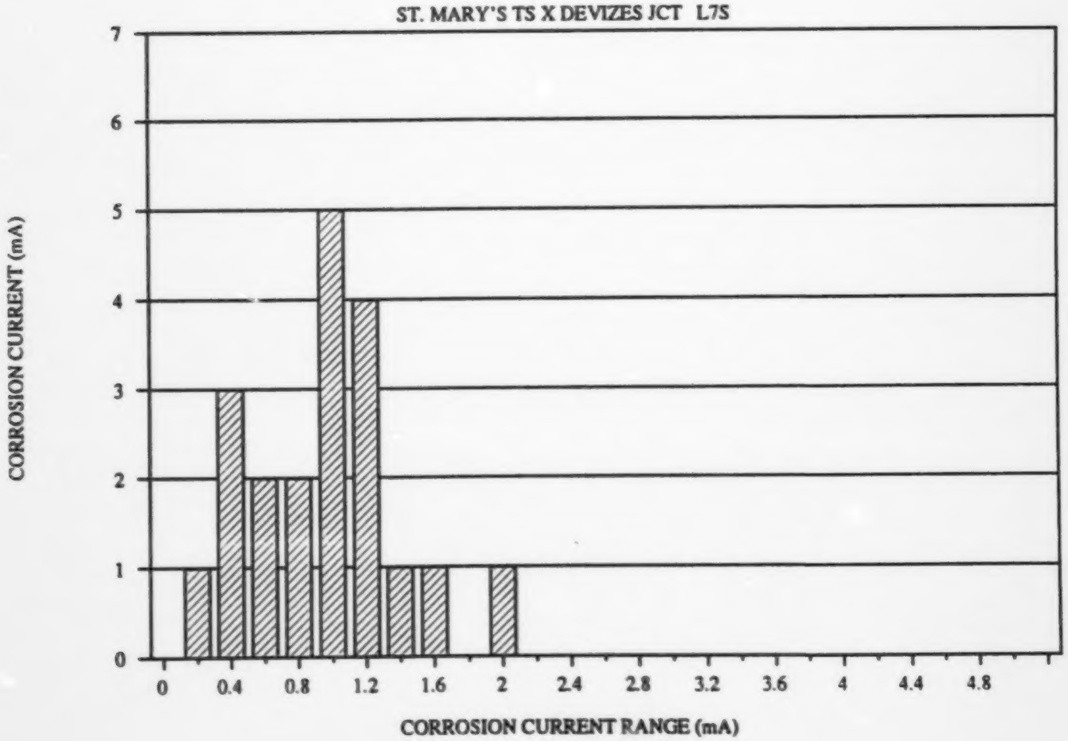


FIGURE A31b

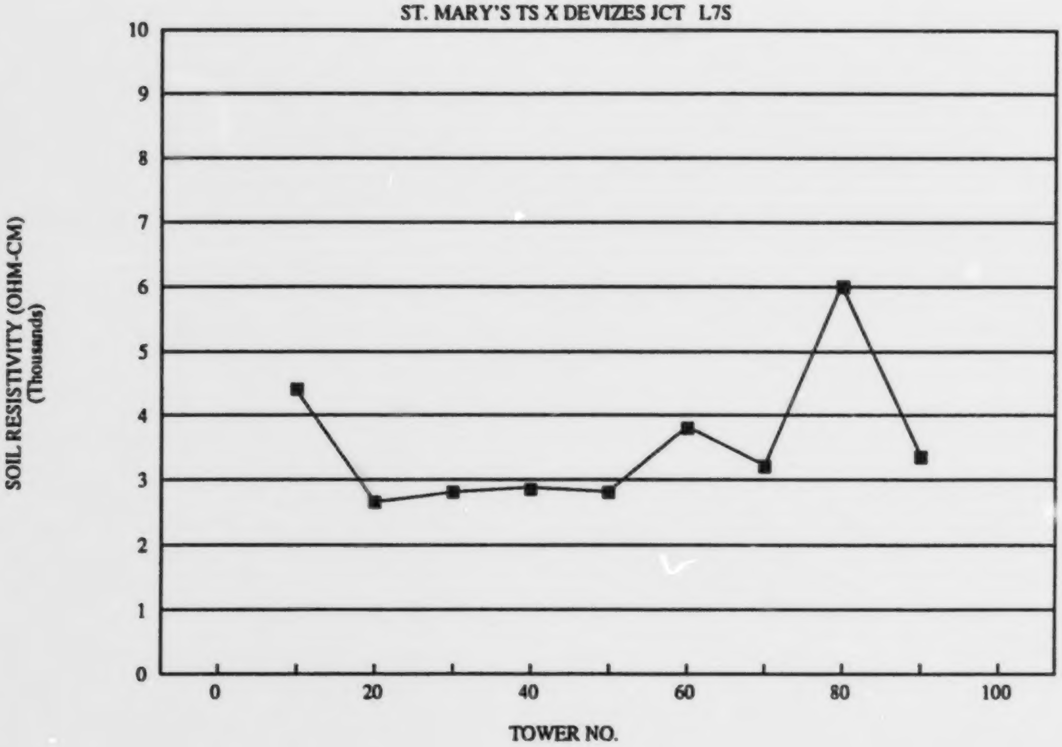

ST. MARY'S TS X DEVIZES JCT L7S
SOIL RESISTIVITY (OHM-CM)
(Thousands)
10
9
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
TOWER NO.

FIGURE A32

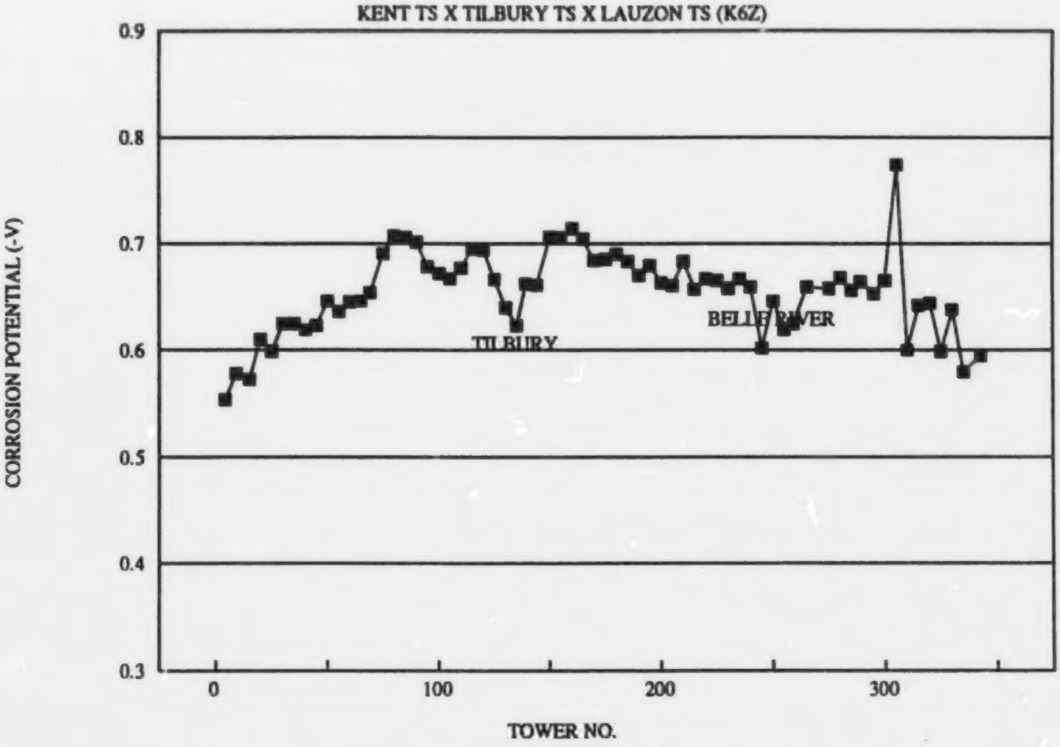


FIGURE A33a

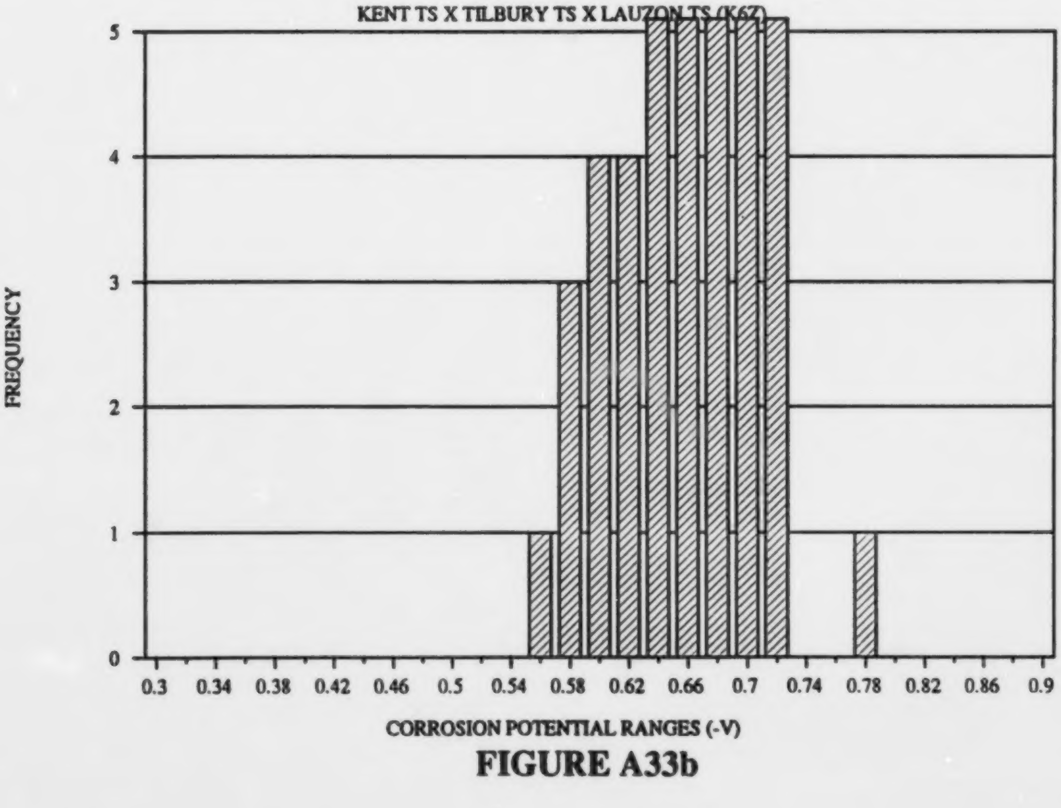


FIGURE A33b

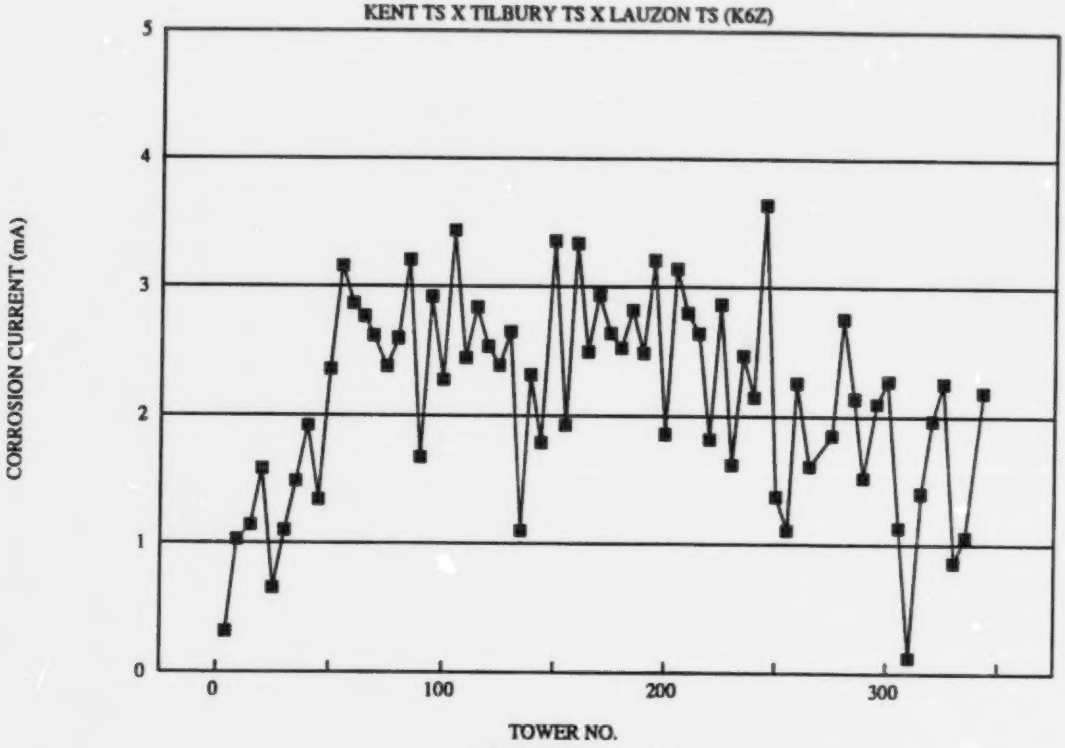


FIGURE A34a

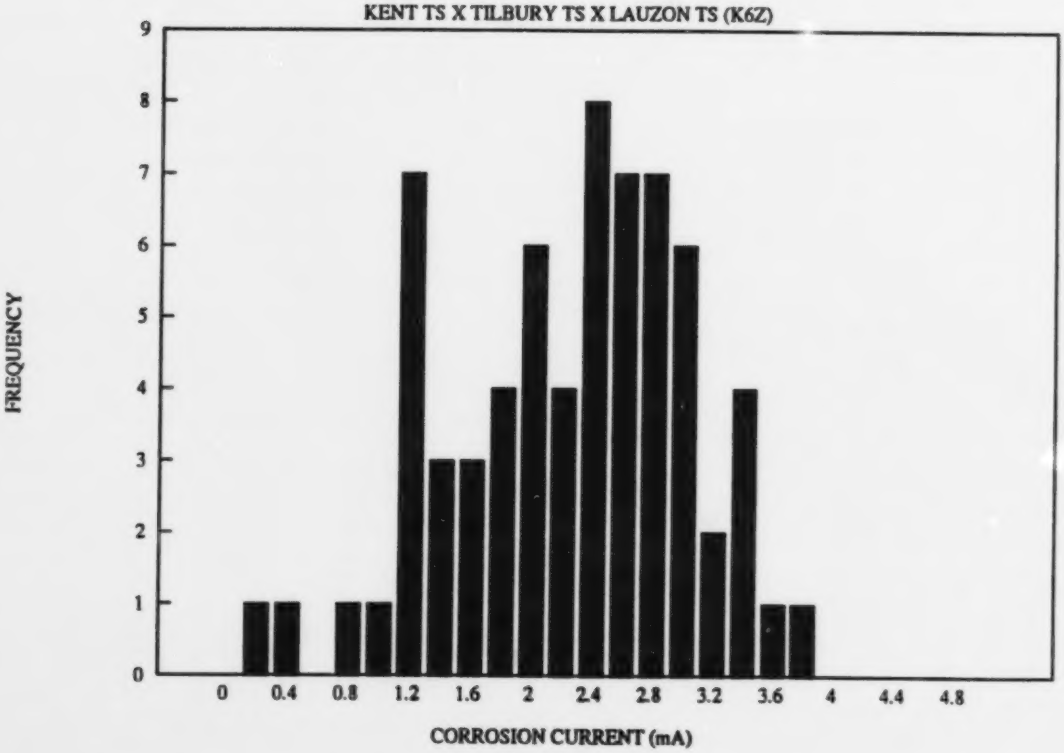


FIGURE A34b

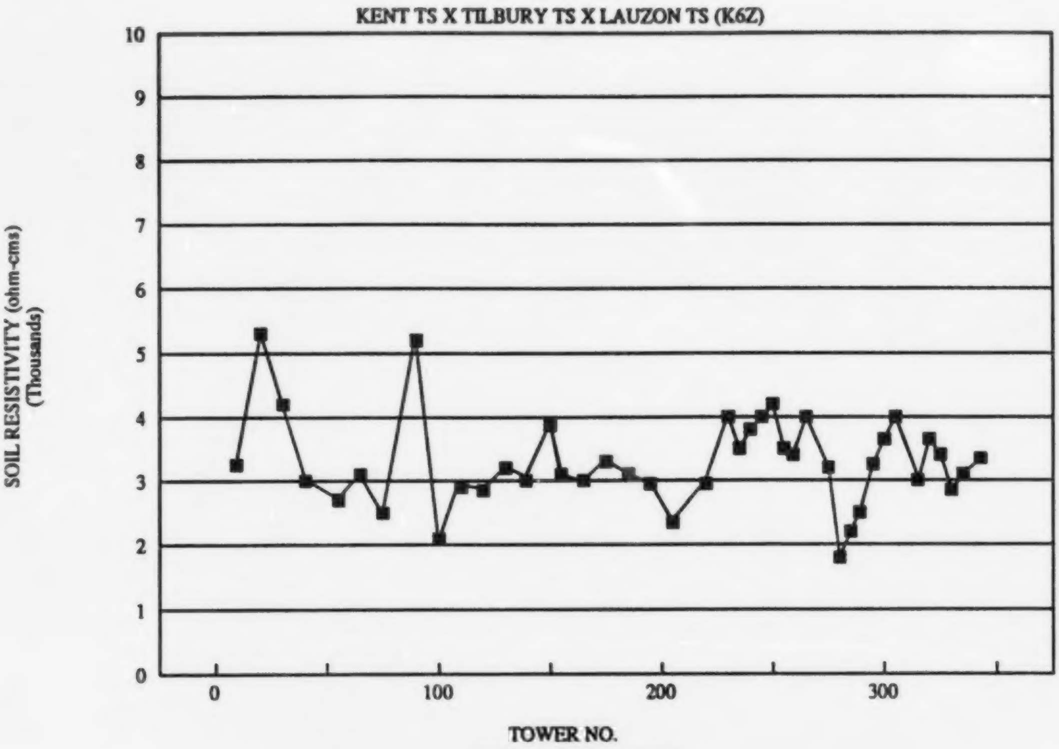


FIGURE A35a

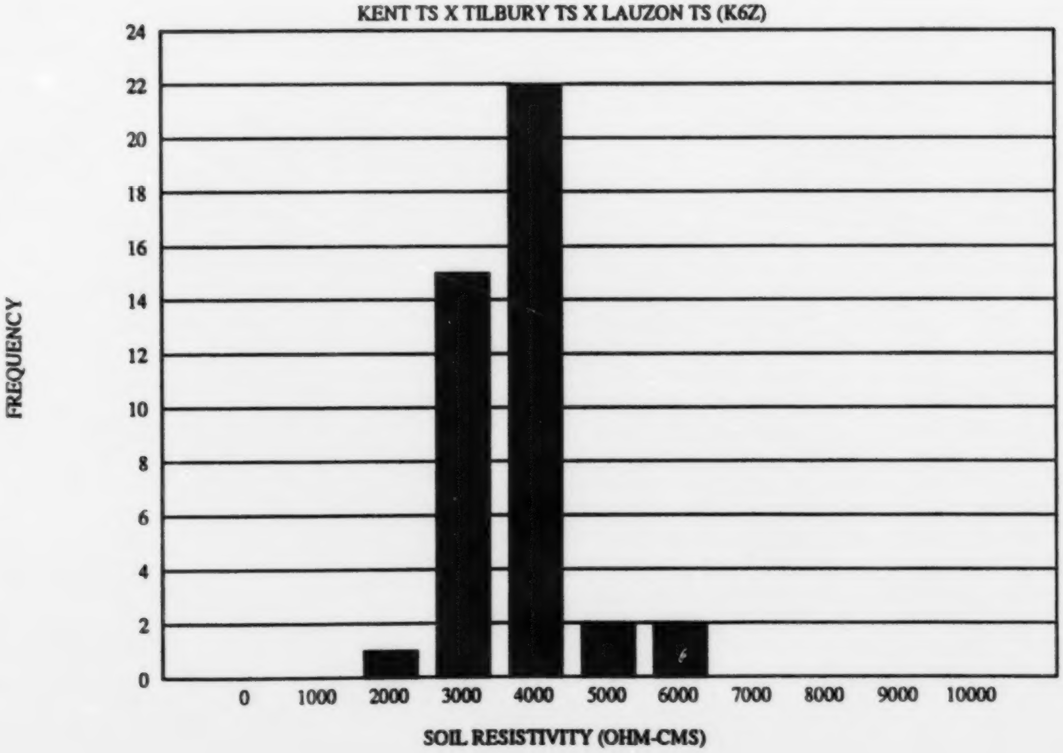


FIGURE A35b

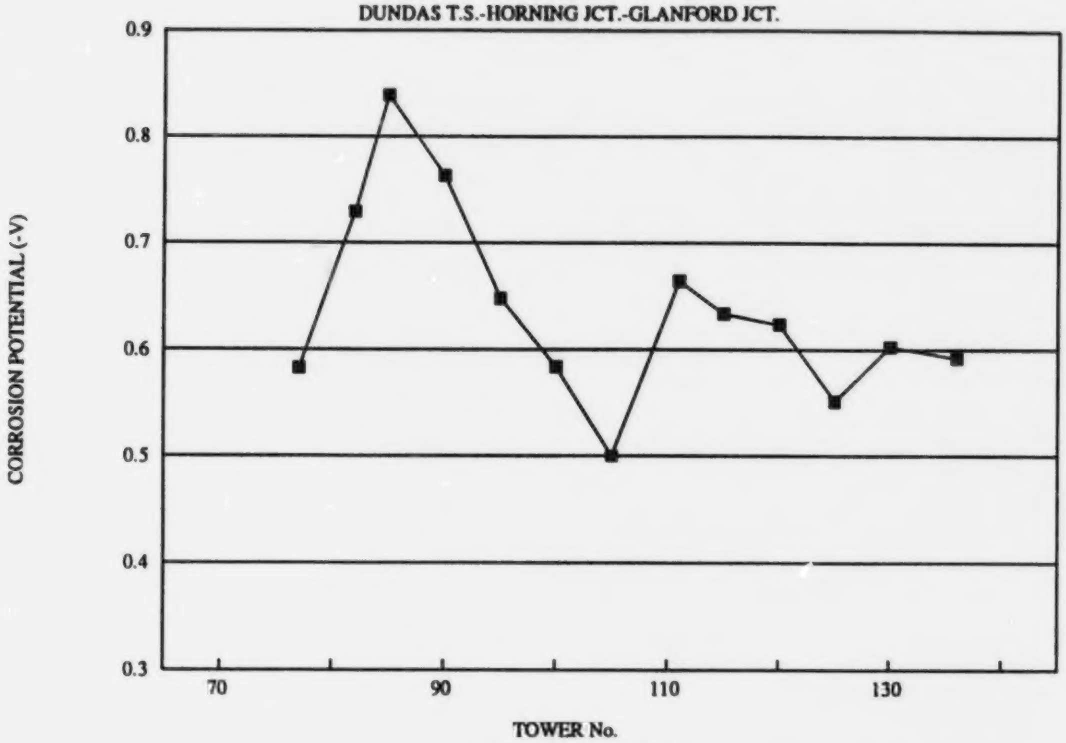


FIGURE A36a

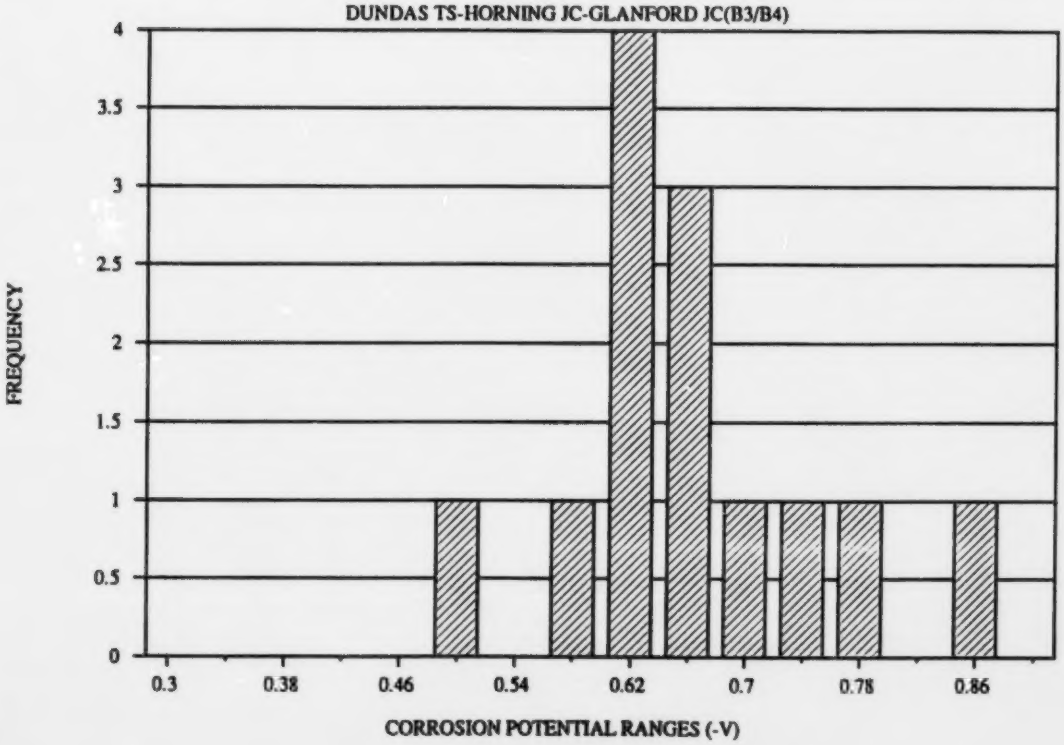


FIGURE A36b

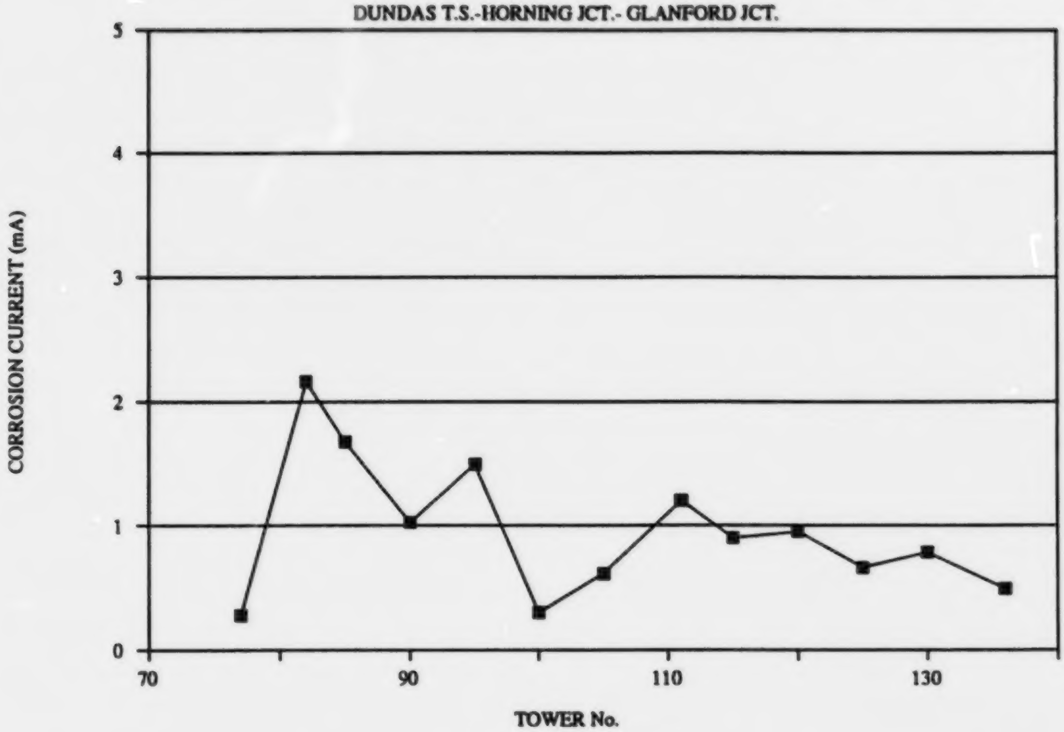


FIGURE A37a

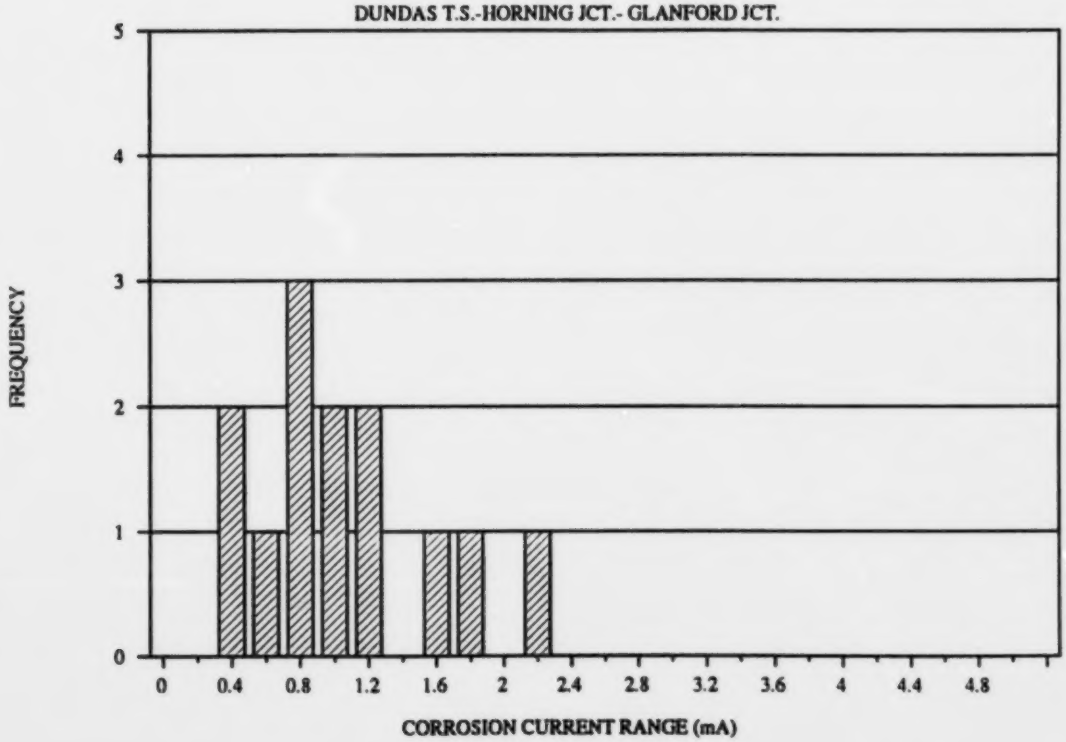


FIGURE A37b

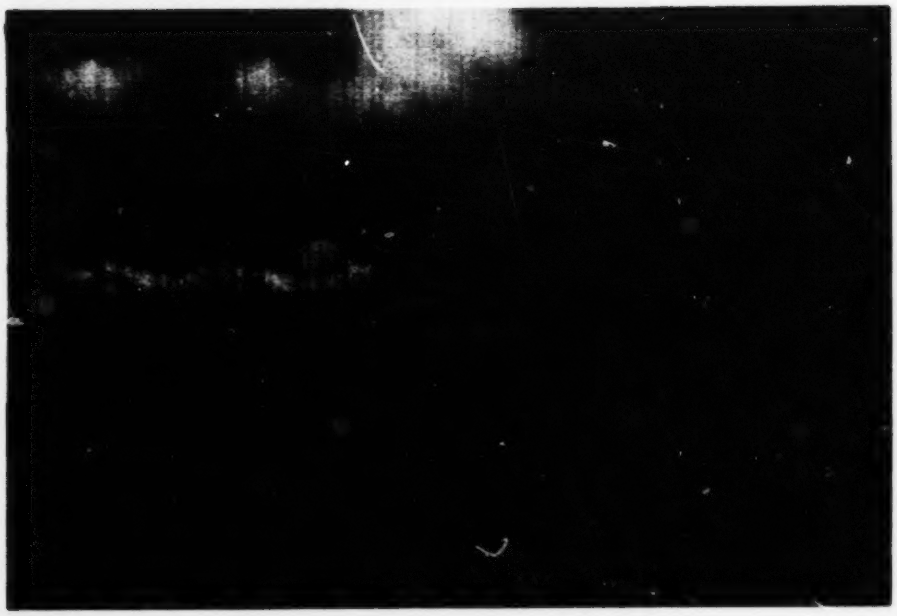


FIGURE A38

CIRCUITS Q2A AND A11T (RIGHT TO LEFT)

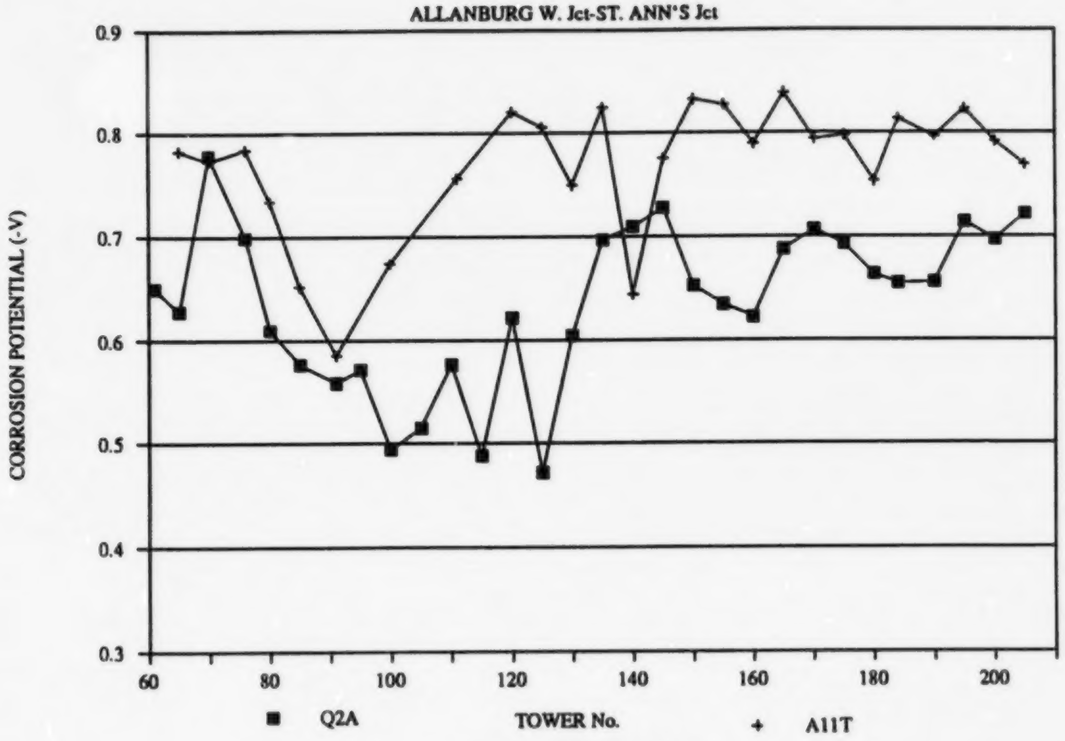


FIGURE A39a

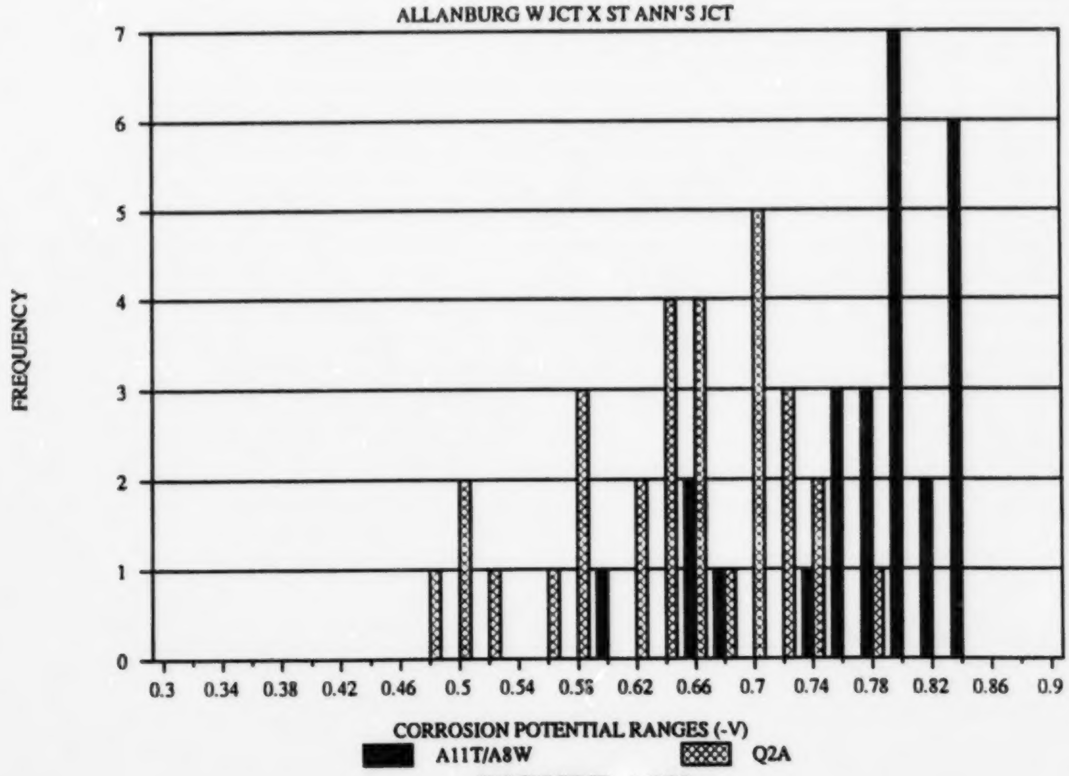


FIGURE A39b

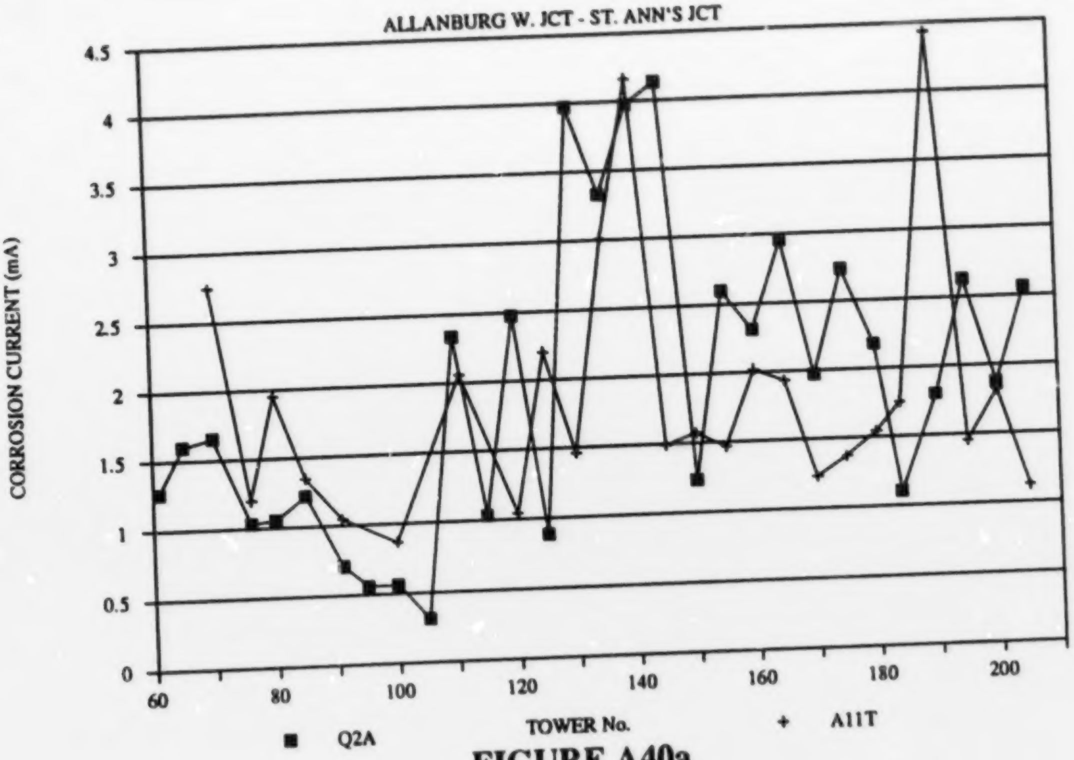


FIGURE A40a

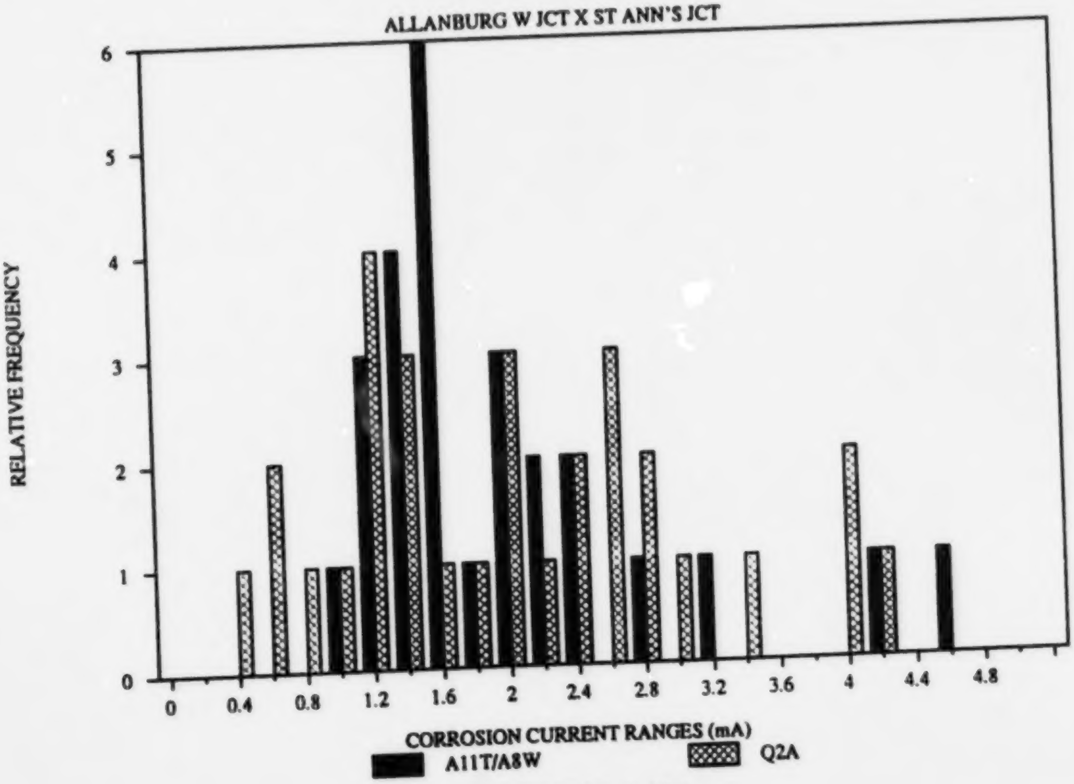


FIGURE A40b

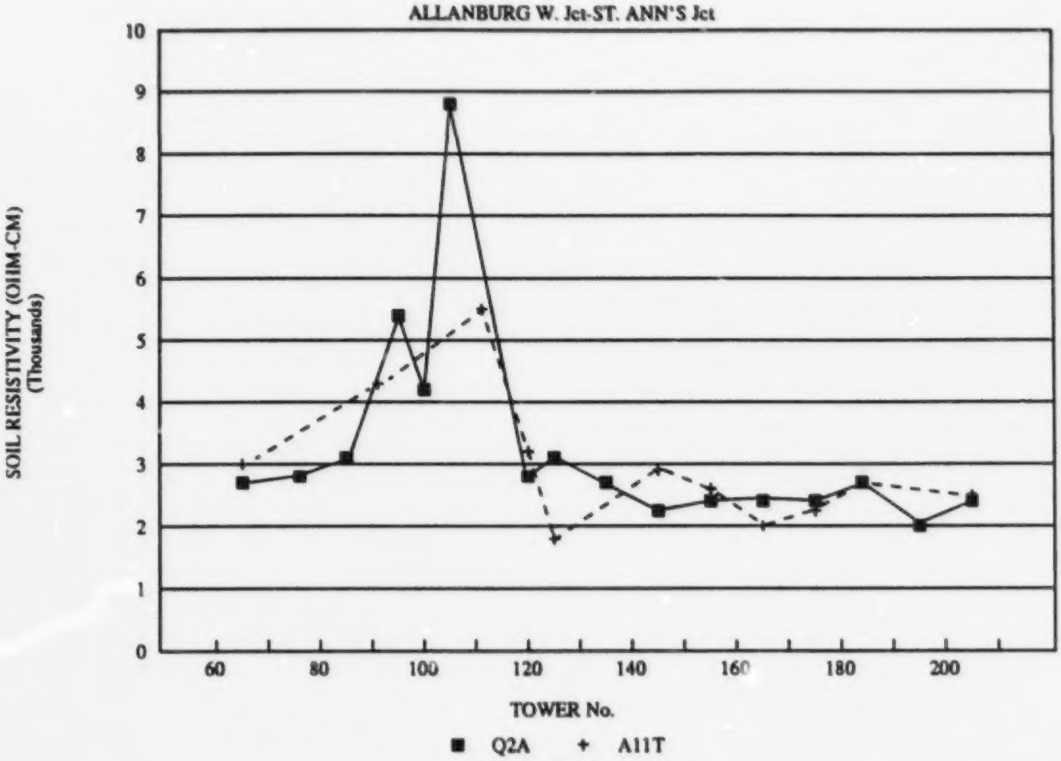


FIGURE A41a

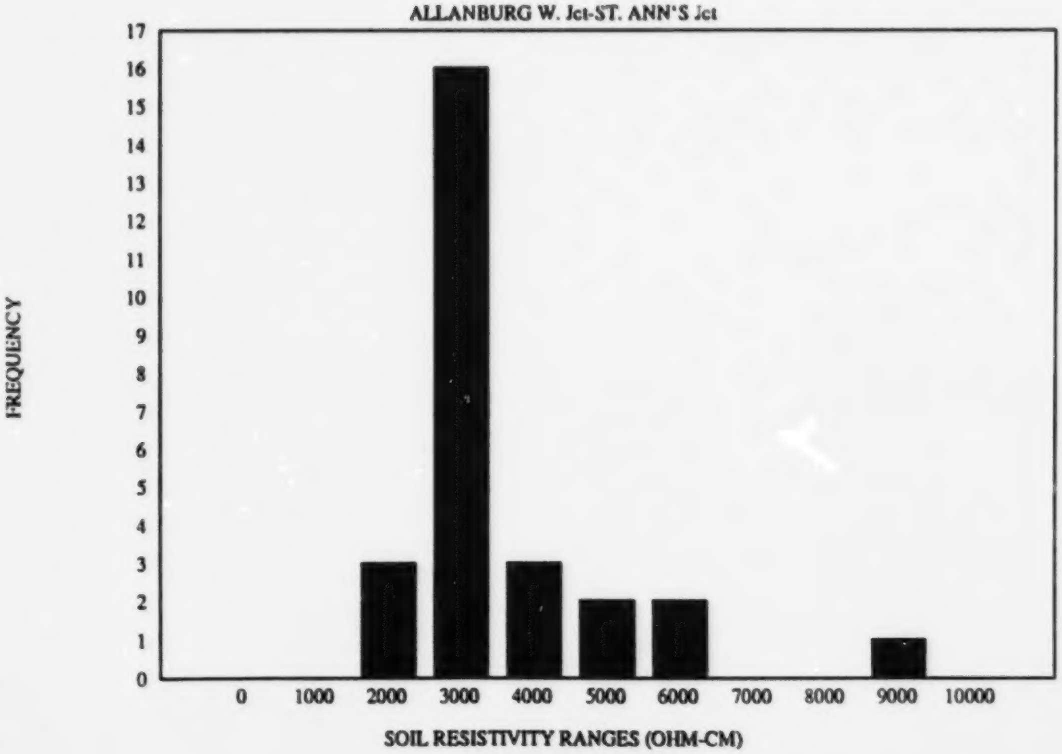


FIGURE A41b

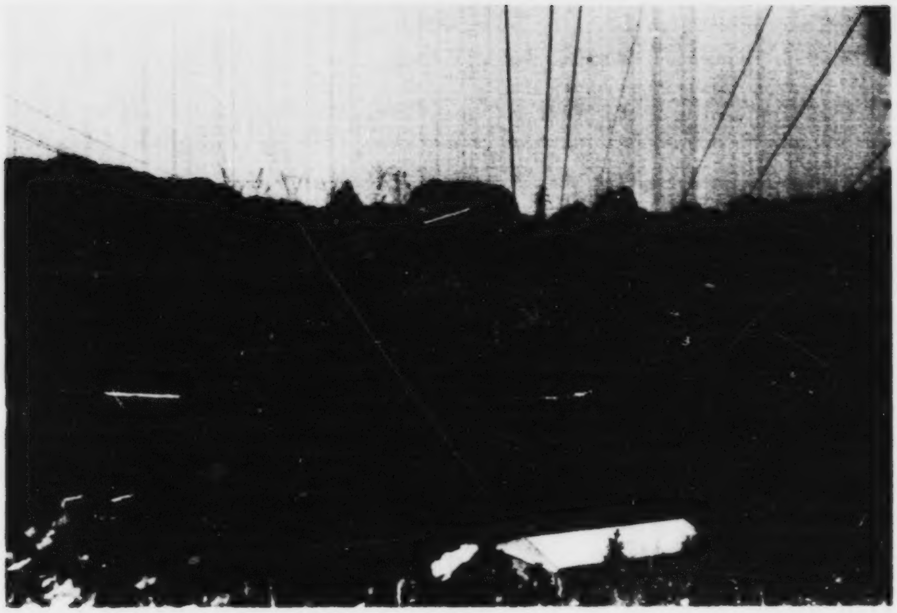


FIGURE A42

CIRCUITS Q2A AND A11T WEST OF ALLANBURG W. JCT

FIGURE A43

CIRCUIT Q2A - TOWER 61

FIGURE A44

CIRCUIT Q2A - TOWER 91

FIGURE A45

CIRCUIT Q2A - TOWER 91

FIGURE A46

CIRCUIT Q2A - TOWER 100

FIGURE A47

CIRCUIT A11T - TOWER 74

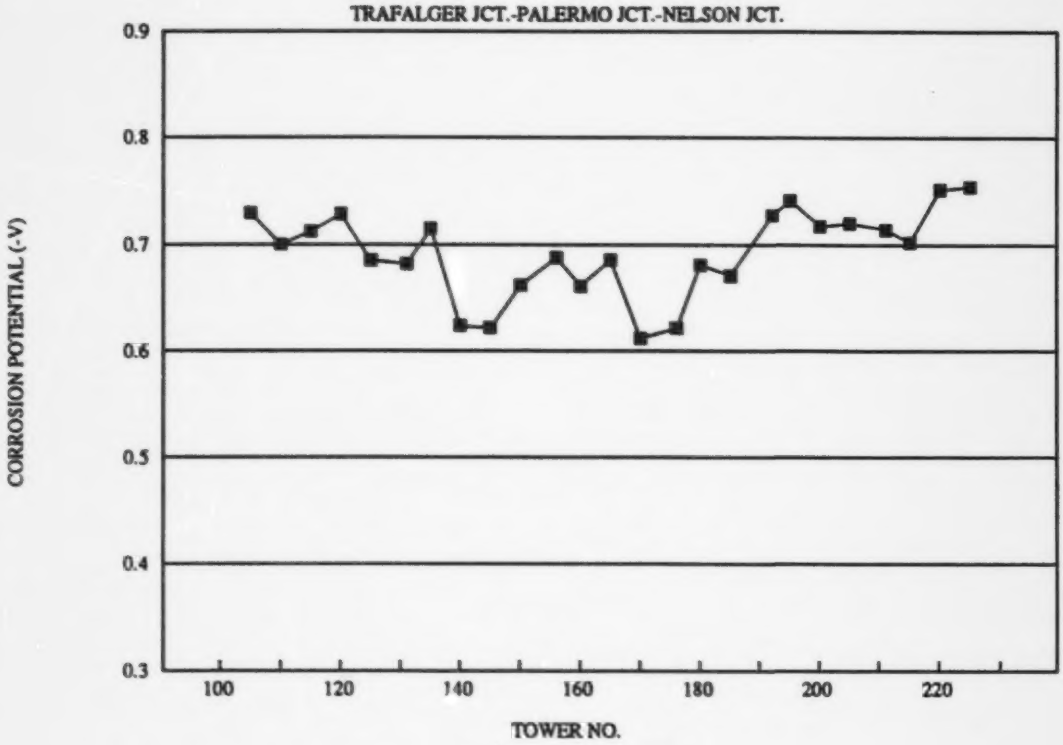


FIGURE A48a

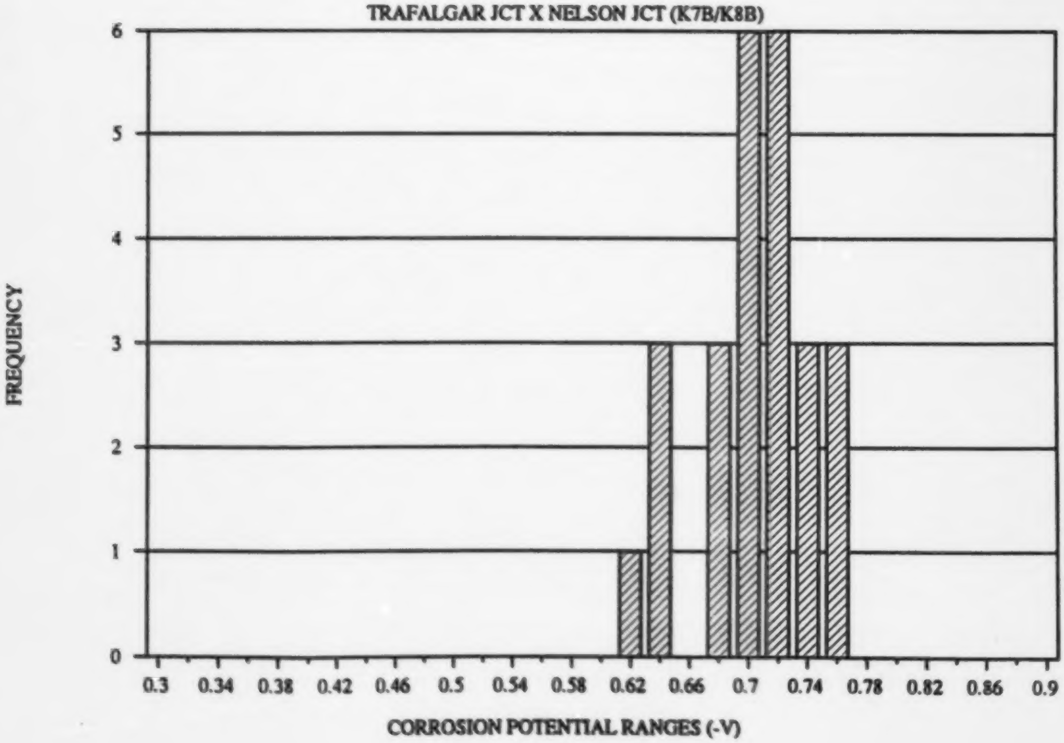


FIGURE A48b

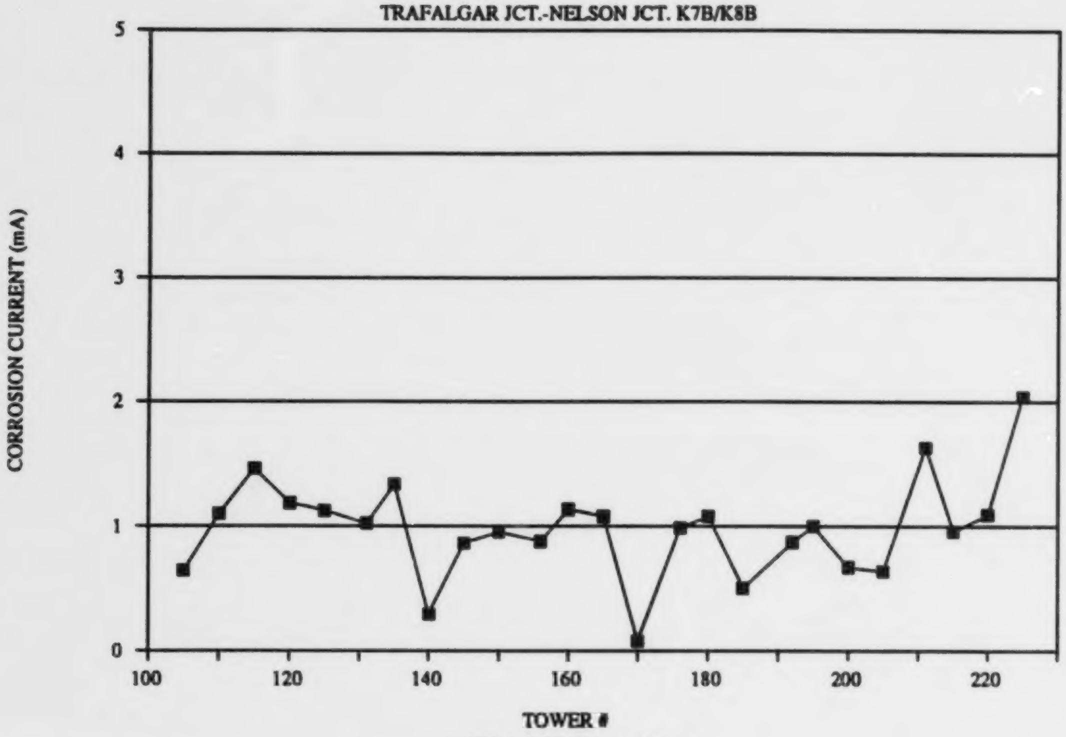


FIGURE A49a

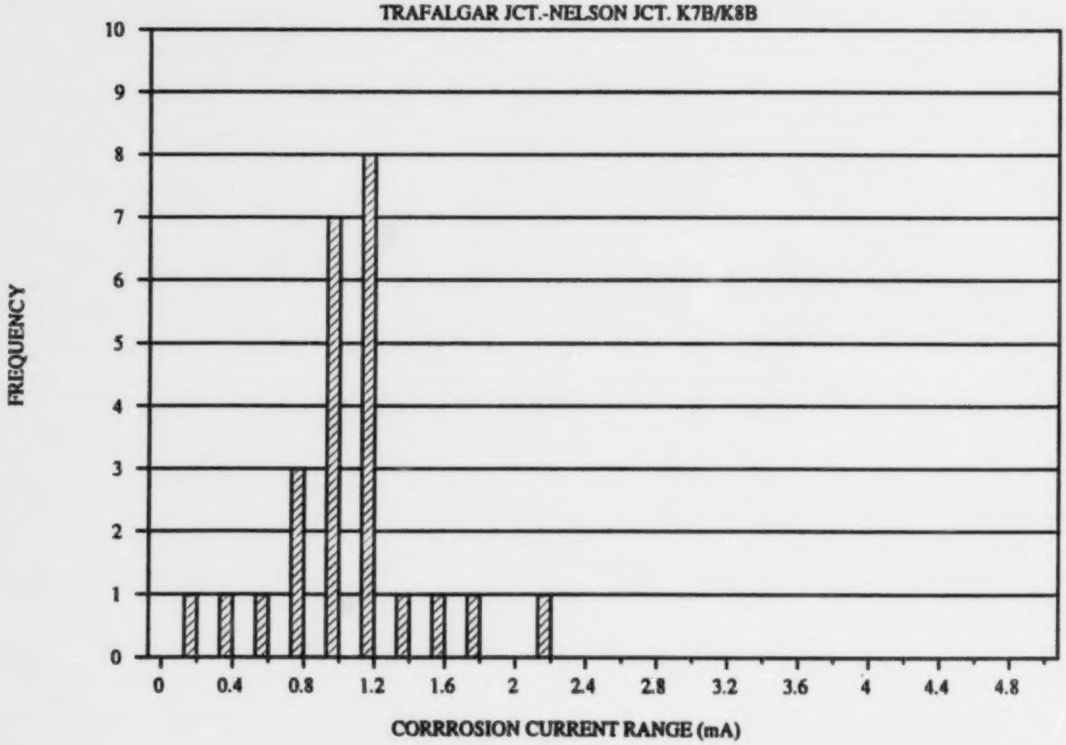


FIGURE A49b

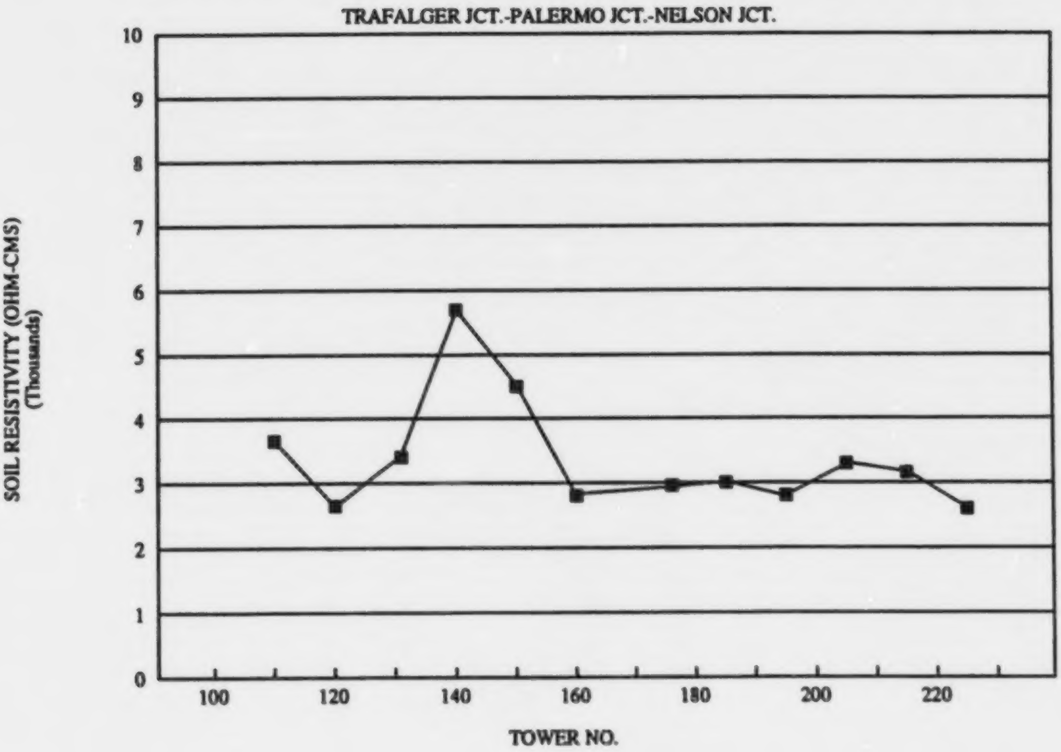

TRAFALGER JCT.-PALERMO JCT.-NELSON JCT.
SOIL RESISTIVITY (OHM-CMS)
(Thousands)
0
1
2
3
4
5
6
7
8
9
10
100
120
140
160
180
200
220
TOWER NO.

FIGURE A50

FIGURE A51

CIRCUIT K7B/K8B - TOWER 200

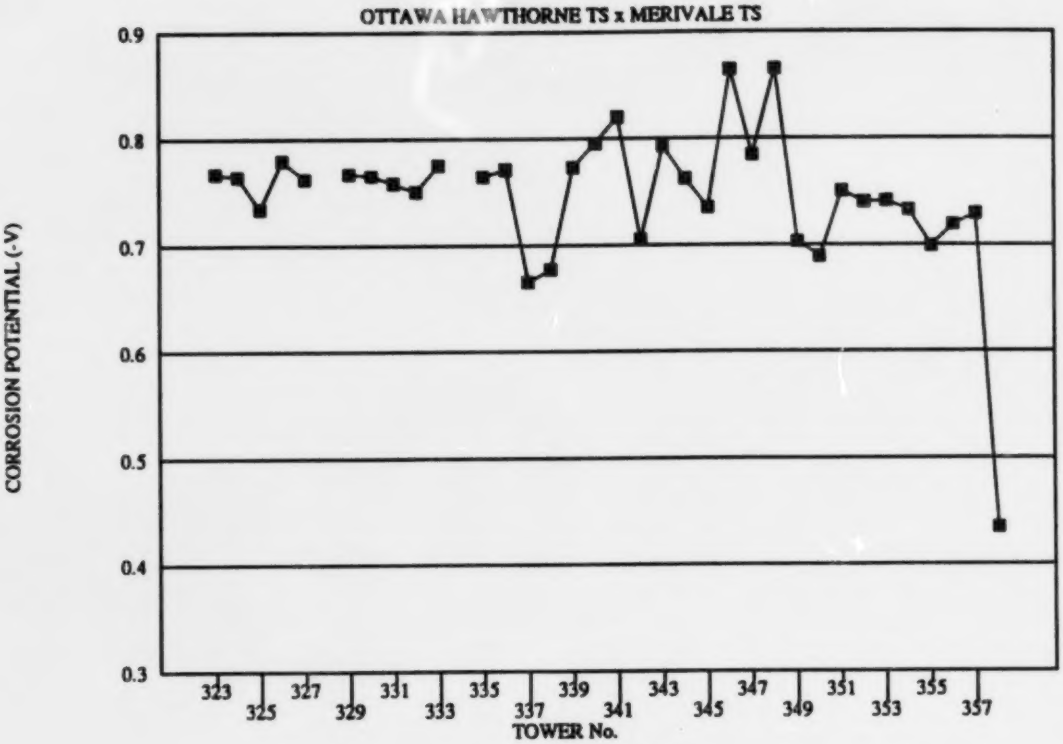

OTTAWA HAWTHORNE TS x MERIVALE TS

FIGURE A52a

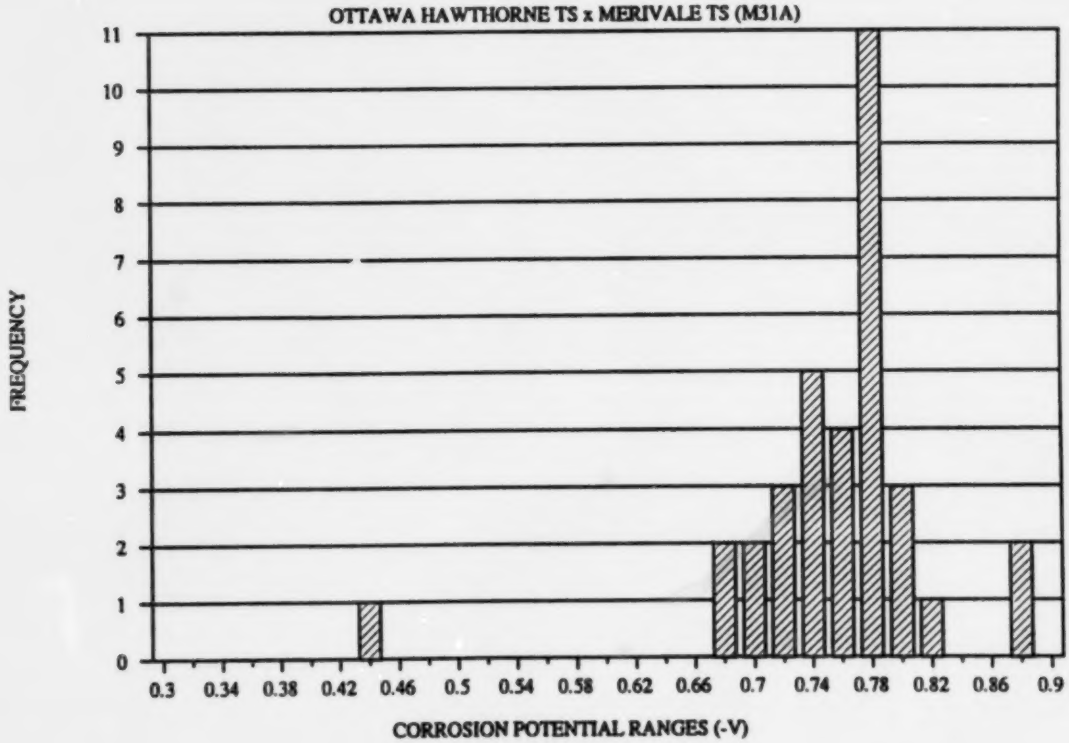

OTTAWA HAWTHORNE TS x MERIVALE TS (M31A)

FIGURE A52b

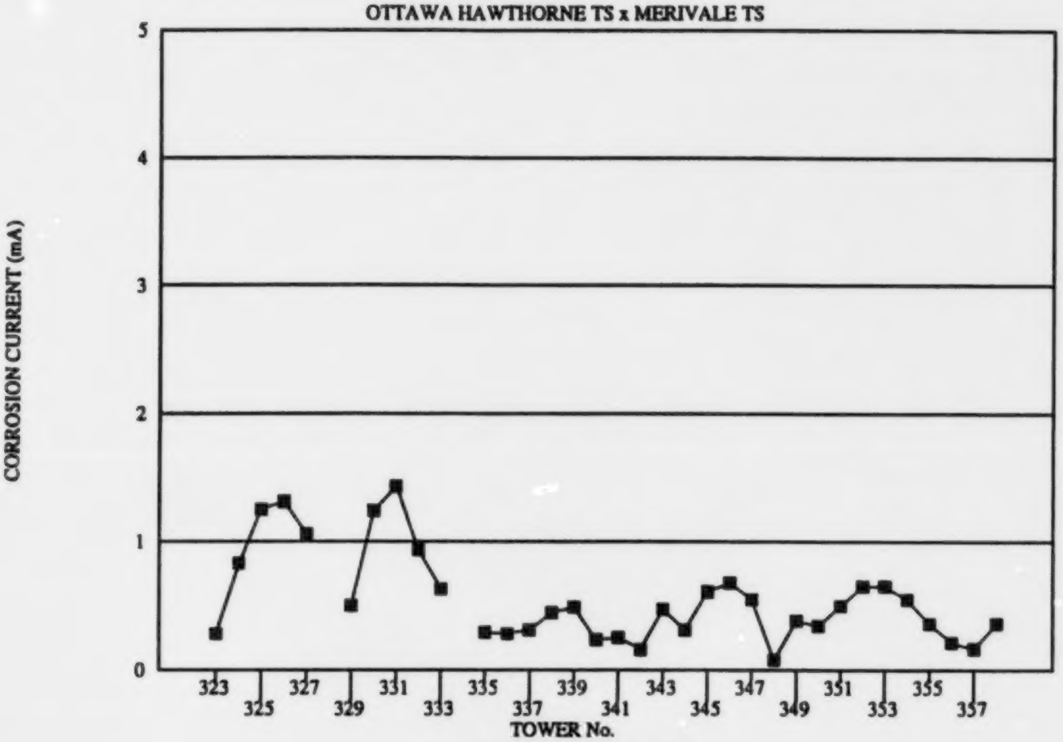


FIGURE A53a

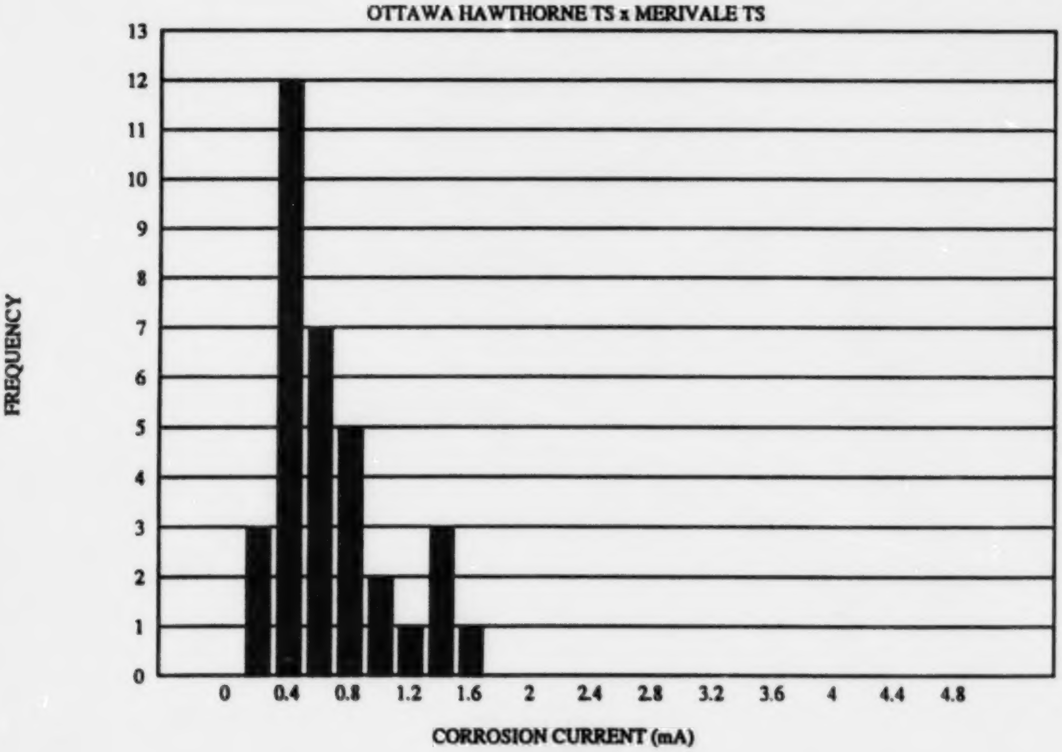


FIGURE A53b

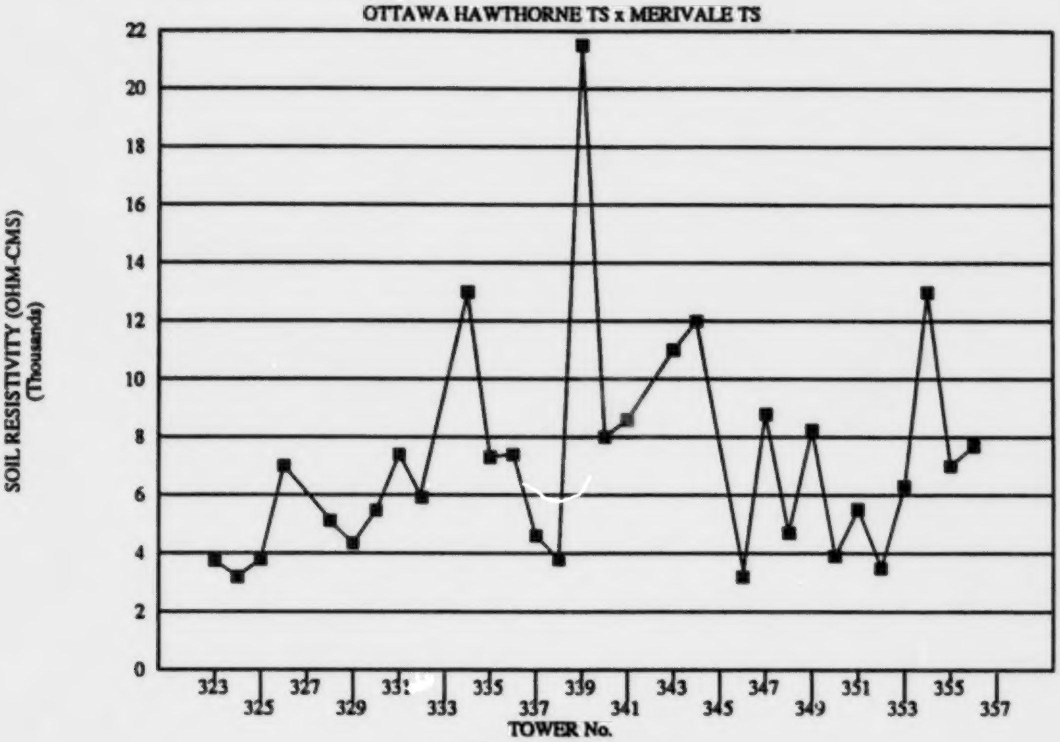

OTTAWA HAWTHORNE TS x MERIVALE TS

FIGURE A54a

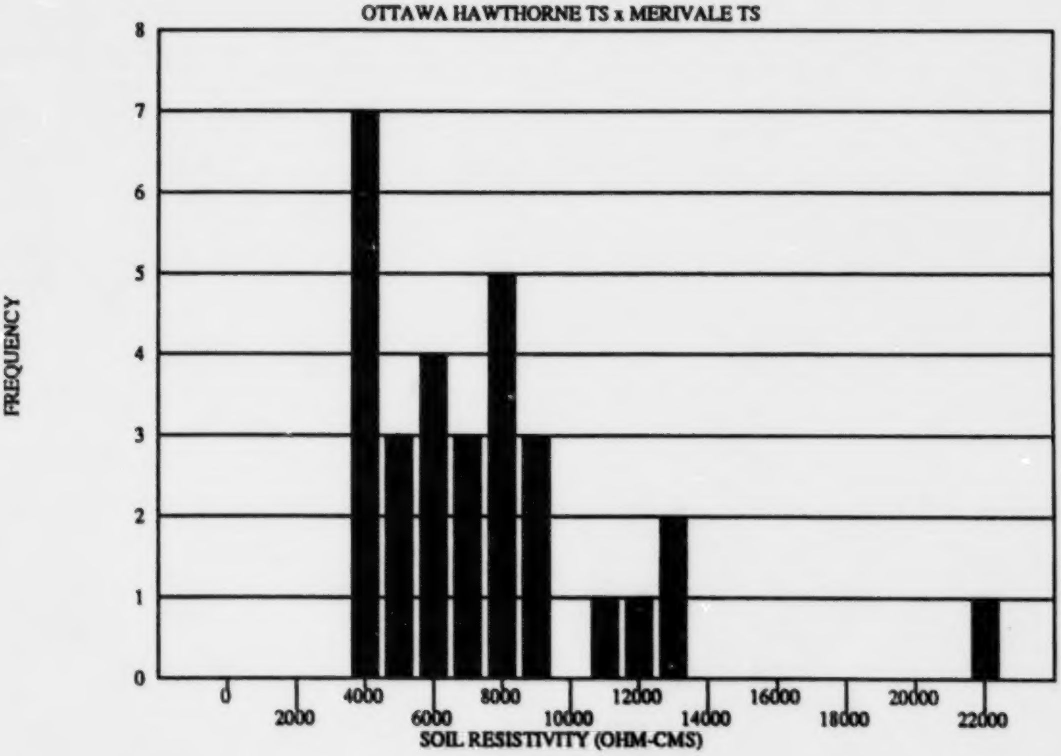

OTTAWA HAWTHORNE TS x MERIVALE TS

FIGURE A54b